A modified coherence method for flow prediction in a compound channel

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A Modified Coherence Method for Flow Prediction in a Compound Channel

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June 2, 2017

Certificate of Examination

Roll Number: *215CE4285*

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We the below signed, after checking the dissertation mentioned above and the official record book (s) of the student, hereby state our approval of the dissertation submitted in partial fulfilment of the requirements of the degree of *Master in Technology* in *Civil Engineering Department* at *National Institute of Technology Rourkela*. We are satisfied with the volume, quality, correctness, and originality of the work.

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June 2, 2017

Supervisors' Certificate

This is to certify that the work presented in the dissertation entitled *A Modified Coherence Method for Flow Prediction in a Compound Channel* submitted by *Sarjati Sahoo*, Roll Number 215CE4285, is a record of original research carried out by him under my supervision and guidance in partial fulfilment of the requirements of the degree of *Master in Technology* in *Civil Engineering Department*. Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

Place: Prof. K. K. Khatua

Date: (Supervisor)

Dedicated To

My Parents

Sarjati Sahoo

Declaration of Originality

I, Sarjati Sahoo, Roll Number 215CE4285 hereby declare that this dissertation entitled Flow Analysis in Compound Channel presents my original work carried out as a Master student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section "Reference" or "Bibliography". I have also submitted my original research records to the External Examiner for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

June 2, 2017 *Sarjati Sahoo*

NIT Rourkela

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Sarjati Sahoo

Abstract

The present thesis is a result of physical and numerical research undertaken by the author to understand the flow characteristics like depth-averaged velocity distribution, boundary shear stress distribution, discharge, etc. of an asymmetric compound channel with differential roughness. Two sets of experiments have been conducted on an asymmetric compound channel in which both the main channel and flood plain are of trapezoidal cross-section. For the first set of experiments, the main channel was kept smooth whereas the flood plain was made rough by laying plastic mat on its bed to achieve differential roughness. The second set of experiments have been conducted on the same asymmetric compound channel but with different roughness condition. The main channel was kept as it is, but the roughness of flood plain again changed by fixing small gravels on it. Using micro-ADV, three dimensional velocity data have been collected from the main channel flow. To get the flow velocity of flood plain flow, Pitot was used. Boundary shear stress values were also measured using Preston tube technique for the compound channel.

Depth-averaged velocity distributions and boundary shear stress distributions for all flow depths of two sets of experiments for the whole asymmetric compound channel section were plotted and analysed. Energy correction factors and momentum correction factors for all flow depths of the two sets of experiments were calculated. Weighted divided channel method (*WDCM*), which was developed by Lambert and Myers (1998) was applied to both set of experiments and the values of weighting factors for flood plain and main channel were calculated. A wide range of data sets, which includes symmetrical and asymmetrical compound channels with homogeneous as well as differential roughness, were considered in this study to check the accuracy of Coherence method, which was first developed by Ackers (1991). A new model has been developed to evaluate discharge adjustment factor (*DISADF*), from which discharge can be predicted easily. The new is found to be capable of predicting the discharge with satisfactory results by resulting an average error of 4.6248% for symmetrical compound channel data sets considered for this study and 4.0927% for all the asymmetrical compound channels. The prediction capacity of the model has been validated with experimental data sets of other researchers, FCF data sets and natural river data sets.

Keywords: Compound Channel; Correction factors; WDCM; Coherence Method; DISADF

Contents

List of Figures

List of tables

Nomenclature

b	Base width of main channel
b_f	Flood plain base width
B	Width of compound channel at flood plain bed level
h	Depth of main channel
H	flow depth
A	Wetted area of cross-section
P	Wetted perimeter
α	Width ratio (B/b)
δ	Aspect ratio (b/h)
D_r	Relative depth ((H-h)/H)
S_0	bed slope/longitudinal slope
S_c	Main channel side slope
U	Point / local velocity
U_d	Depth-averaged velocity
ρ	Density of water
F_r	Froude number
R_e	Reynold's number
ξ	Weighting factor used in WDCM
R^2	coefficient of determination
R	hydraulic radius of channel = A/P
Q	discharge of the channel
P	wetted perimeter of the channel
n	Manning's roughness co-efficient
α_1	Energy correction coefficient
β_1	Momentum correction coefficient
g	acceleration due to gravity7
f	Darcy-Weisbach friction factor

U_m	Mean velocity
Δh	Head difference between two limbs of the inclined manometer
θ	Inclination angle of the manometer to the horizontal base
Δp	Difference between static and dynamic pressure
τ_b	Boundary shear stress
N_f	Number of flood plains
A_{mc}	Area of main channel
A_{fp}	Area of flood plain
P_{mc}	Wetted perimeter of main channel
P_{fp}	Wetted perimeter of flood plain
f_r	Friction factor ratio

Abbreviations

ADV	Acoustic Doppler Velocimeter
COH	Coherence
DCM	Divided Channel Method
DDM	Diagonal Division Method
FCF	Flood Channel Facility
HDM	Horizontal Division Method
RANS	Reynolds averaged Navier-Stoke's equation
SCM	Single Channel Method
VDM	Vertical Division Method
WDCM	Weighted Divided Channel Method

Chapter-1

Introduction

1.1 Background

In the prehistoric era, the fluid-human interaction had been strictly limited to the water. A remarkable portion of water resources, which affect the humankind in both constructive and destructive way, is in form of open channels such as rivers and streams. From ancient times many civilizations like Indus valley civilization, Sumerian, Egyptian civilization etc. were established in the valleys of rivers. In present day also there are many cities Cuttack, Kolkata, Delhi, Agra London, Tokyo, Moscow, Baghdad etc. are situated on the river valleys. Despite of the fear of possible floods, river valleys always attracted human beings. This is mainly due to the availability of water for different uses and transportation, advantages and benefits related to soil fertility for agriculture.

Flow in open channels are characterized by the existence of a free surface. The pressure on the free surface in constant and atmospheric at every point on the free surface. All open channels have a bottom slope and hence gravity force is the main force causing the flow. Open channels include both natural rivers and streams as well as man-made structures like irrigation canals, sewers and laboratory flumes.

For the approximate prediction, controlled and well-planed use of natural and man-made open channels, measurement of different properties of flow like water-depth, conveyance, velocity, boundary shear stress etc. are very much essential. These measurements are taken into design consideration by two methods, which are direct method and numerical method. By direct method, flow properties are measured using sophisticated equipment. In numerical method, models are developed to predict the nature and properties of flow as a source of indirect method.

1.2 Types of open channel

Different types of open channels are classified as

1.2.1 Type 1

1. *Natural Channel* – All rivers and streams. Generally non-uniform in size and shape.
2. *Artificial Channel* – Man-made channels like irrigation canals, drains, sewers and laboratory flumes which are uniform in shape and size.

1.2.2 Type 2

1. *Prismatic Channels* – A channel having uniform cross-section and slope in the reach. All artificial channels are prismatic.
2. *Non-prismatic Channels* – When cross-section and slope vary with space and time. All the natural rivers and streams are non-prismatic.

1.2.3 Type 3

1. *Rigid Boundary Channels* – Channels having a rigid (not movable) bed and sides known as rigid boundary channels. Lined canals, sewers and non-erodible unlined canals come in this category. No problem of sediment.
2. *Mobile Boundary Channels* - The boundary of these types of channels are composed of loose sedimentary particles, which move under the action of flowing water. Sediment problem exits.

1.2.4 Type 4

1. *Small Slope Channels* – Channels having s bottom slope less than 1 in 10 are known as small slope channels (Chow, 1959).
2. *Large Slope Channels* – Channels having a bottom slope more than 1 in 10 are called as large slope channels (Chow, 1959).

1.2.5 Type 5

1. *Simple Channel* - A channel having only main channel.
2. *Compound Channels*- A channel having both main channel and flood plain. Again compound channel is of three types.

   (a). *Symmetrical* – Compound channel having equal width of flood plains on both sides of main channel.

(b). *Unsymmetrical*- Compound channel having unequal width of flood plains on both sides of main channel.

(c). *Asymmetrical*- Compound channel having a single flood plain on either side of main channel.

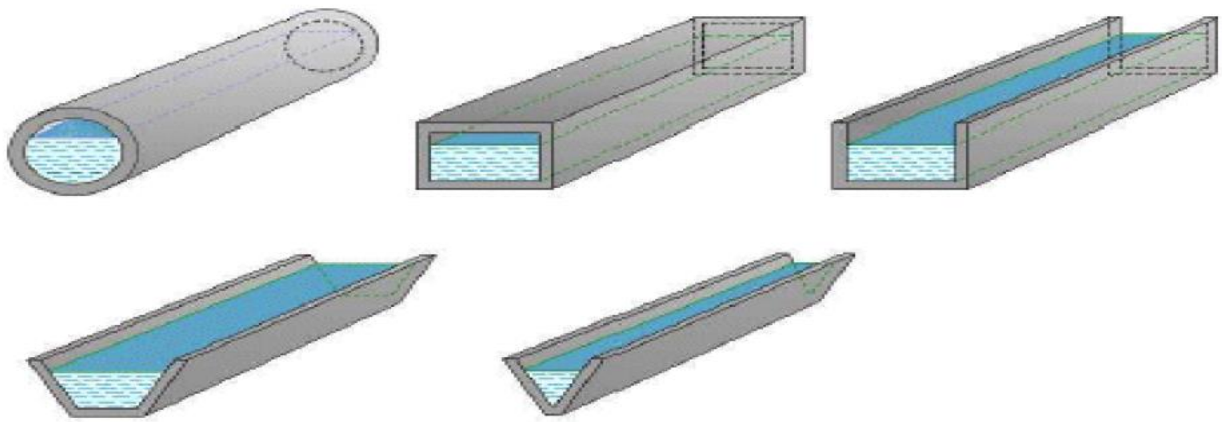


Fig 1.1: Various types of simple channels.

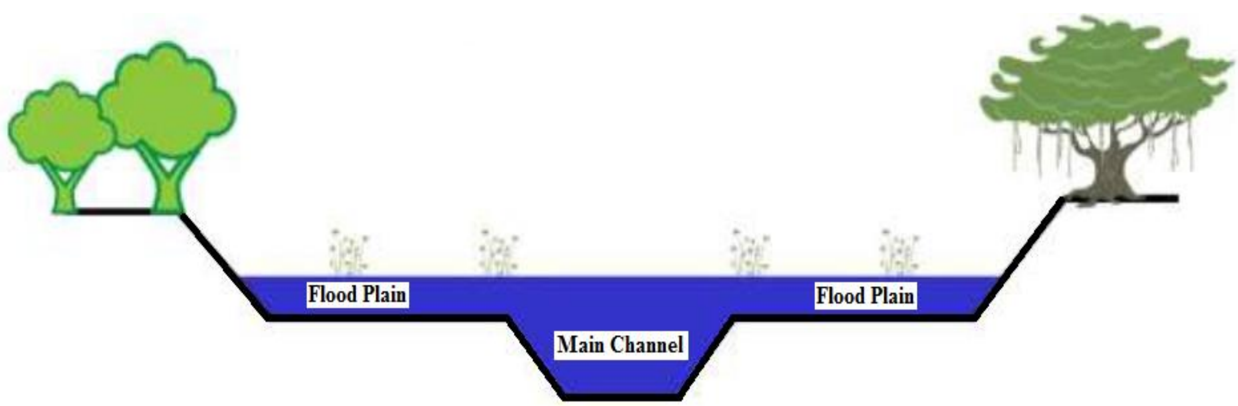


Fig 1.2(a): Symmetrical Compound Channel

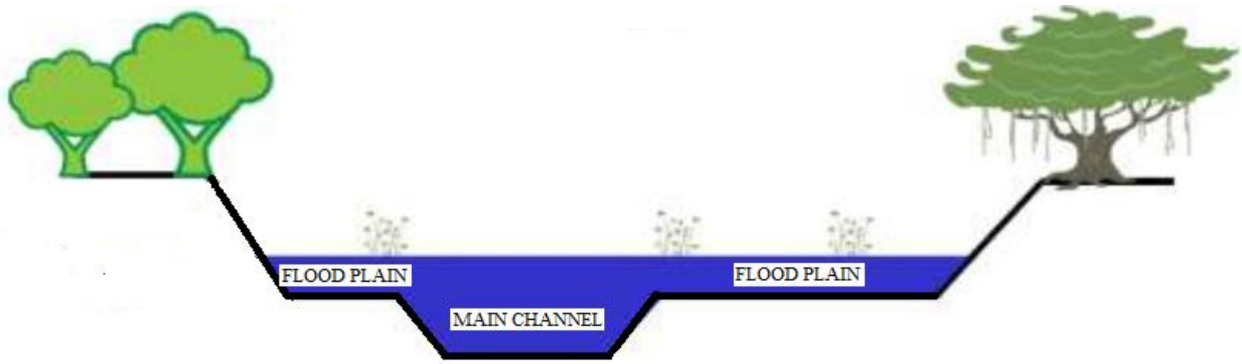


Fig 1.2(b): Unsymmetrical Compound Channel

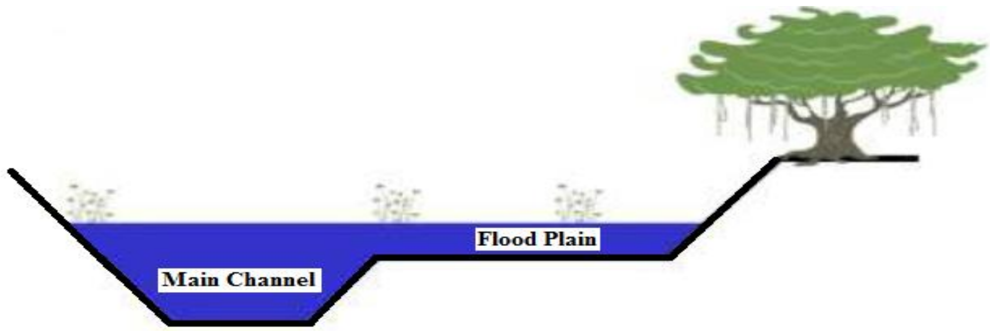


Fig 1.2(c): Asymmetrical Compound Channel

1.3 Classification of Flow

Open channel flow can be classified into many types and described in various ways which are given below.

1.3.1 Based on variation with time *t*

(i) *Steady Flow:* When the flow parameters like discgarge (Q), velocity (U) and depth (y) do not change with time.

Mathematically $\frac{\partial Q}{\partial t} = 0,\ \frac{\partial U}{\partial t} = 0,\ \frac{\partial y}{\partial t} = 0$

(ii) *Unsteady Flow:* When the flow parameters change with time, i.e.,

$$\frac{\partial Q}{\partial t} \neq 0,\ \frac{\partial U}{\partial t} \neq 0,\ \frac{\partial y}{\partial t} \neq 0$$

1.3.2 Based on variation with space *x*

(i) *Uniform Flow:* When the flow parameters do not change with space *x*, i.e.,

$$\frac{\partial Q}{\partial x} = 0, \quad \frac{\partial U}{\partial x} = 0, \quad \frac{\partial y}{\partial x} = 0$$

(ii) *Non-Uniform Flow:* When the flow properties change with space, i.e.

$$\frac{\partial Q}{\partial x} \neq 0, \quad \frac{\partial U}{\partial x} \neq 0, \quad \frac{\partial y}{\partial x} \neq 0$$

It is also called as varied flow.

Again non-uniform flow is of three types:

(a) *Gradually Varied Flow (GVF):* If the changes in depth of flow are gradual, the flow is said to be gradually varied. e.g. the back water curve behind a weir or a dam.

(b) *Rapidly Varied Flow (RVF):* In rapidly varied flow, depth changes are more in small distances. e.g. Hydraulic Jump.

(c) *Spatially Varied Flow (SVF):* If to any existing flow system some flow is abstracted or added, it is called as spatially varied flow.

1.3.3 Based on Froud number

(i) *Subcritical Flow:* When the Froud number for a flow is less than one i.e. $F_r < 1$

(ii) *Critical Flow:* When the Froud number for a flow is equal to one i.e. $F_r = 1$

(iii) *Supercritical Flow:* When the Froud number for a flow is greater than one i.e. $F_r > 1$

Where Froud number is the ratio of inertia force to gravity force.

1.3.4 Based on Reynold's number

(i) *Laminar Flow:* The value Reynold's number is less than 500 i.e. $R_e < 500$.

(ii) *Transitional Flow:* Value of Reynold's number is in between 500 to 2000 i.e. $500 < R_e < 2000$.

(iii) *Turbulent Flow*: In this case, Reynold's number is greater than 2000 i.e. $R_e > 2000$.

1.3.5 Based on Co-ordinate system or plane of flow

(i) *One-dimensional Flow:* All the properties of flow may be demonstrated as function of time and single space co-ordinate only. But actually one dimensional flow never exists.

(ii) *Two-dimensional Flow:* The properties of flow are function of time and 2 space co-ordinates (*X and* Y), but constant in *Z* direction.

(iii) *Three-dimensional Flow:* Generally the flow of fluid is three-dimensional in nature. All the flow parameters vary in all the three co-ordinates.

1.4 Compound Channel

A natural river has two sections, main channel section and flood plain section. When the flow of water inundates the flood plain by exceeding the capacity of main channel, the channel may be called as a compound channel. Generally, most rivers and streams flow in main channel. However, during heavy rainfall when the main channel is incapable of accommodate all the water, then the flood plains are inundated by the excess water. Compound channels are also known as two-stage channels.

Generally, the roughness character of flood plains are more than the main channel of a river. During overbank flow conditions, the flow becomes more complicated due to the dissimilarities in hydraulic and geometric properties of main channel and flood plain. Both velocity and boundary shear stresses are higher in deeper main channel than the shallow flood plain as flood plains give more resistance to the flow in overbank stage. Due to the difference in velocity of deep main channel and shallow flood plain, lateral momentum transfer occurs between main channel and flood plain, which further complicates the flow process (Sellin, 1964; Myers and Elsawy, 1975; Rajaratnam and Ahmadi, 1979; Knight and Demetriou, 1983).

As it is quite difficult to obtain precise and very reliable field measurement of velocity and shear stress in rivers during flood, which is very unsteady during flood, well designed flumes in laboratory under steady flow conditions are preferred to acquire information about the flow structure of compound channel. These information are very much essential in design of various numerical models for solving practical problems like bank erosion in rivers, stable channel design, flood management, etc.

There are many studies available on symmetrical compound channels but a few on asymmetrical compound channels. Therefore, in the research work presented here, experiments were conducted on an asymmetrical compound channel fabricated in the Hydraulic laboratory of Civil Engineering department, NIT Rourkela. Two sets of experiments were conducted having two different types of roughness material used on flood plain whereas the main channel was kept smooth. For the first set of experiments, plastic mat was used as the roughening material on flood plain having Manning's *n* value of 0.024 and in second set of experiments, small gravels of Manning's *n* value 0.02 were used to make the flood plain rough. Trowel finished cement concrete was used to construct the main channel bed, which was taken as smooth having Manning's *n* value of 0.01. Natural rivers seldom bear a uniform roughness throughout the main channel and flood plain. In river, the materials constructing the bed and boundary of main channel and flood plain are very much different in maximum cases. So to attain natural condition in laboratory, here the experimental asymmetric compound channel was made non-homogeneous in terms of roughness condition of main channel and flood plain. The influence of differential roughness of main channel and that of flood plain on various flow properties were studied here for the asymmetric compound channel.

1.5 Objective of the Research Work

1. To study the depth averaged velocity distribution and boundary shear stress distribution in an asymmetric compound channel.
2. To compute the energy correction factor and momentum correction factor in asymmetrical two-stage channels.
3. To evaluate the weighting factor used in Weighted Divided Channel Method for main channel and flood plain of asymmetrical compound channels.
4. To predict the discharge by using Coherence method for both symmetrical and asymmetrical compound channels.
5. To develop models to evaluate the discharge adjustment factor (*DISADF*) for both symmetrical and asymmetrical channels, by which the discharge can directly be predicted.
6. To validate the model with data sets of previous researchers and some natural rivers.

1.6 Dissertation Layouts

The dissertation has been divided into six chapters including introduction. Chapter 1 consists of general introduction, chapter 2 includes previous literatures, explanation of experimental setup and procedures are presented in chapter 3, chapter 4 consists the experimental results and discussions, theoretical analysis and model development are given in chapter 5 and chapter 6 includes concluding remarks and scope of future work.

Chapter 1 gives a brief introduction to importance of open channels, types of open channels, classification of flow under various criteria. This chapter also includes the objective of present research work with a background knowledge about compound channels and gives an overview of the work undertaken in the dissertation.

Chapter 2 named as literature review, which gives a glance of existing works of previous researchers in this field. By doing literature review one can gain knowledge and idea about how to do future research work. Here, this chapter incorporates a concise interpretation of the research carried out in straight compound channels based on stage-discharge relationships, depth-averaged velocity distribution, boundary shear stress distribution, new models to predict discharge.

Chapter 3 explains the experimental procedures adopted to design the channel with differential roughness, calculation of bed slope, measurement of flow depth and discharge, collection of three directional velocity data by the help of a micro-ADV and measurement of boundary shear stress using a Pitot tube.

Chapter 4 gives the results of the experiments conducted on the asymmetric compound channel, which includes stage discharge relationships, depth-averaged velocity distribution and distribution of boundary shear stress across the whole compound channel section.

Chapter 5 includes theoretical analysis and model development in which the evaluation of energy correction factor and momentum correction factors for the present experimental asymmetrical compound channel has been done. Application of Weighted Divided Channel method (*WDCM*) and application of Coherence method are done for the present experimental channel. The Coherence method is used to predict the discharge for other symmetrical and asymmetrical compound channels. Models are developed to calculate the discharge adjustment factor (*DISADF*) for both symmetrical and asymmetrical compound channels, which are given in this chapter. Error analysis has been performed for the new developed models against wide range of data sets of laboratory channels as well as natural rivers to check the efficiency of the model.

Chapter 6 includes the concluding remarks and scope for future research work.

Various research work done by the previous investigators, which are referred to in subsequent sections in this study have been cited at the end of the thesis in the reference section.

Chapter-2

Literature Reviews

2.1 General

"What we are today comes from our thoughts of yesterday, and our present thoughts build our life of tomorrow." – Buddha.

Without past there is no future. So without having knowledge about past research no future investigation can be done. In the field of science and innovation, research is a nonstop procedure where the data and discoveries from the past research are sent to the future era in form of published literature. Therefore, before doing any sincere and constructive research work, a detailed literature survey is very much essential. Here, in the present study a concentrated review of literature was done covering both the symmetrical and asymmetrical compound channel cases.

2.2 Compound Channels

This section contains information about the various findings of both symmetrical and asymmetrical compound channels of various researchers, which are summarized below.

Sellin (1964) first explored the momentum transfer mechanism in a two-stage channel. He presented photographs to show the presence of vertices having vertical axis at the junction of main channel and flood plain. He also observed velocity and discharge of the experimental channel under interacting and isolated conditions. He concluded that the velocity in main channel under isolated condition was more than that in the interacting condition.

Myers and Elsawy (1975) studied the flow interaction between main channel flood plain. They assessed the impact of lateral momentum transfer on the velocity of flow on main channel, discharge, boundary shear stress for isolated flood plain flow (non-interacting) and combined main channel and flood plain flow (interacting) in a straight asymmetric compound channel. They found that the increase in maximum shear stress of flood plain was 260%, when the observed boundary shear stress under interacting and non-interacting conditions were compared for the shallowest flood plain depth of their experiments.

Rajaratnam and Ahmadi (1981) conducted experiments on an asymmetrical compound channel having a wide main channel to study the interaction between main channel and flood plain flow. They found that, the region which was affected by the interaction could be treated as shear layer or mixing layer to some extent. They observed that the velocity profiles were similar in the lateral direction in the mixing region. Empirical equations were also developed for velocity and length scales. Due to the interaction between main channel and flood plain, the bed shear stress in the flood plain was increased whereas for main channel the bed shear stress was decreased. They also noted that the average apparent shear stress was a function of ratio of main channel flow depth and flood plain flow depth. This average apparent shear stress was resulted by the main channel flow on the flood plain flow. In the mixing region located on the flood plain, the generated eddy viscosity was found to vary significantly across the mixing region. They also observed that the mixing layer on flood plain was more complex than the mixing region on main channel.

Knight and Demetriou (1983) obtained the results about the discharge characteristics, the boundary shear stress and shear force distributions by doing experiments in a two-stage channel having a rectangular main channel and two symmetrically disposed flood plains. They derived equations to predict the shear in terms of two dimensionless parameters on the flood plain as a percentage of the total shear force. Ancillary equations were also derived using the shear force results from experiment to calculate the transverse and vertical momentum transfer within the cross section. They observed that when the depth of flow was shallow and for wider flood plains, apparent shear force acting on the interface between main channel and flood plain was more. Equations were developed to predict the amount of total discharge flowing in different parts of the compound channel.

Knight and Hamed (1984) performed experiments on a symmetrical rectangular compound channel to know the boundary shear stress distributions in the channel. They considered roughened flood plains to observe the effect of dissimilar roughness properties of flood plains and the main channel on the process of transverse momentum transfer. They also derived equations, which gives the shear force on the flood plains as a percentage of the total shear force in terms of four dimensionless parameters. They also demonstrated the impact of transfer of momentum between various sub-areas on the distribution of longitudinal velocity in vertical and transvers direction.

Prinos and Townsend (1984) measured the relative accuracies of traditional discharge prediction methods by conducting experiments on a symmetrical compound channel and similar observations of other researchers were also compared. They found that the single channel method was underestimating the discharge whereas the divided channel methods were overestimating the discharge when the difference in velocity between the deep main channel and shallow flood plain was more. Therefore, they suggested a new method to predict the discharge by including the momentum transfer between the main channel and flood plain into account. They found that the method developed by them was giving decent results for the conditions they examined. They also stated that the accuracy of their method could be improved by developing more accurate friction factor relationships for compound channels.

Myers and Brennan (1990) used the results of first series of experiments from the Flood Channel Facility (FCF) to study the characteristics of flow in simple and compound channel having smooth boundaries. They demonstrated the effect of momentum transfer from main channel to flood plain on the discharge capacity of compound channel and main channel sections. It has been found that due to the momentum transfer, the discharge capacity of compound channel and main channel and the velocity above bank full depth reduced whereas the same parameters increased for flood plain. They compared the flow resistance relationships, which were in terms of Manning's and Darcy-Weisbach resistance coefficients of the compound channel section, main channel and flood plain section with the single channel shapes. They observed that the resistance coefficients for main channel and flood plain were increased and decreased respectively due to the momentum transfer mechanism.

Wormleaton and Merrett (1990) presented SERC FCF experimental results to find out discharge and boundary shear stress distribution in symmetrical compound channel with varying flood plain width & roughness. Number of methods were assumed to calculate several standard discharges at different location of the interface between main channel and floodplain sub areas. Large errors were found in total and mostly in discharge, which increase rapidly with floodplain width and roughness. A modified method was then introduced by incorporating ϕ-indices, which was enumerated by tentative regression analysis to minimize the error, and it gives more accurate results than the standard methods for calculating discharge component. This new method resulted in improved accuracy of discharge calculation.

Ackers (1993) proposed a new improved method to predict discharge in compound channels called as Coherence method. A parameter was introduced called coherence, which represents the hydraulic similarity between main channel and flood plain. He observed that the flow was divided into four well-defined flow regions, which depends on the relative depth of flow. For each region, to predict the discharge, new design formulae had been proposed after correcting the effect of interaction effect. These equations were then applied and affirmed over an extensive range of data sets.

Naot et al. (1993) demonstrated the hydrodynamic behavior of turbulent flow in a rectangular compound channel to the flood plain flow depth, roughness properties, symmetry and to the Reynold's number of the channel. Numerical simulation was done on the flow in the four asymmetrical channels experimented by Tominaga and Nezu in 1991. Other symmetrical channels were also considered for numerical simulation. By combining the energy-dissipation model and algebraic stress model, which was suggested by Naot and Rodi in 1982, modelling for turbulence was done. The parabolic pressure correction algorithm of Patankar and Spalding was used to solve the three-dimensional flow in the experimental channel. The researchers also gave examples to estimate the friction factors and momentum transfer between main channel and flood plain flow.

Parthasarathy and Muste (1994) conducted experiments over a flat stationary bed having different roughness by making the flow turbulent with Reynolds number 60,000. Velocity of flow was measured using 2D Laser Doppler Velocimeter. The results showed that the planes of maximum velocity and zero Reynolds stress were not coinciding. A lot of diffusion of momentum and kinetic energy also took place from rough to smooth surface. They observed that the vertical transfer of fluctuation of velocity near the bed decreased when the roughness of cover was increased.

Tsai and Ettema (1994) developed a revised eddy viscosity model, as the vertical circulation of turbulent vortex viscosity in one-dimensional completely developed asymmetric compound channel flow could not be acquired by conventional eddy viscosity model. For the significant properties of flow in channels of differential roughness, they used a two-power law equation to depict vertical dissemination of flow velocity. They gave a formula for a constant dissemination of eddy viscosity with positive sizes of turbulent vortex viscosity for asymmetric compound channel flows using the new model, which utilizes the two-power law expression. They stated that this model could be used to estimate turbulent eddy viscosity in asymmetric compound channel.

Lambert and Myers (1998) presented a method called weighted divided channel method (WDCM) for estimating the stage discharge relationship in a straight compound channel. The method was formulated by examining the variation in the mean velocity of the main channel and the floodplain section resulted due to the interaction of momentum between the sub-sections. A single parameter (ξ) was introduced which was applied to the sectional velocities anticipated by the vertical and horizontal division technique to deliver a transitional velocity which more accurately gives the observed velocity in both the primary channel and the floodplain. An estimation of ξ =0.5 has been discovered suitable for smooth compound channels and ξ = 0.2 for two-stage channels with a high degree of roughness on floodplains.

Bradbrook et al. (2001) studied open channel junctions in laboratory with help of a three dimensional, elliptic solution of the Reynolds- Averaged Navier-Stokes (RANS) equations. They compared their expression with the results of experiments on a tributary junction of asymmetric type. After comparing, they found that the quantitative details of the flow structure in laboratory experiments were better than that of model. However, their model produced some good statistically remarkable features of the results from experimentation. They used their newly developed expression to understand the structure of flow in a junction by keeping one of the tributaries angled at 45^0, both with and without an elevation difference in the angled tributary. The model was also used to find out the effect of junction angles, bed discordance and ratio of mean velocities in the tributary channels on flow structures.

Hosseini (2004) studied and proposed a new method to predict discharge in straight compound channels having homogeneous roughness. The new model was developed by analyzing the experimental results of a United Kingdom Flood Channel Facility (UK-FCF). Two correction coefficients were introduced namely *a* and *b,* which were applied to the main channel mean velocity and flood plain mean velocity predicted by vertical division method in order to estimate more correct values of the main channel and flood plain mean velocities. The coefficients *a* and *b* were expressed in terms of two dimensionless quantity of the channel, coherence and relative depth. This method was compared to Weighted Divided Channel method, which was developed by Lambert and Myers by considering the experimental data sets of other researchers. The present method was found to be providing good results than the Weighted Divided Channel method.

Yang et al. (2007) conducted experiments on a small-scale laboratory flume with various types of vegetation on flood plain to understand the hydraulics of flow in a two-stage channel with vegetated flood plains. They described the flow patterns by using various types of vegetation such as tree, shrub and grass. To vegetate the flood plain for experiment, they selected plastic grass, duck feathers and plastic straws as model grass, shrubs and trees respectively. To estimate the local flow velocities, a three-dimensional Acoustic Doppler Velocimeter was used for various types of vegetation and non-vegetated flood plains also. They observed that the measured streamside velocity distributions were following the logarithmic distribution for non-vegetated flood plain conditions, whereas the velocity distributions followed an S-shaped profile in case of vegetated flood plains. They also analyzed the effect of various types of vegetation on secondary currents, magnitude of turbulence and Reynold's shear stresses. They found that, in the main channel side-slope regions the secondary current cells were not strong at higher relative depths.

Huttoff et al. (2008) proposed a new method to predict the discharge of compound channel called as the Interacting Divided Channel Method (IDCM). The method was developed based on parameterization of the interface stress between main channel and flood plain of a compound channel. In the method, they included the lateral momentum transfer based on physical scaling arguments. They compared the data from other experiments and found satisfactory results. They concluded that the one-dimensional flow models for river engineering could be used to know the effects of lateral momentum transfer as their method IDCM gave encouraging results.

Moreta and Martin-Vide (2010)

They developed a dimensionally sound expression depending on the square of the velocity gradient between the main channel and the floodplains, i.e., apparent friction coefficient. The variation of apparent shear coefficient was also analyzed with the geometrical and roughness ratios. They also presented and validated a generalized formulation to predict the apparent shear stress for a wide range of laboratory data which they got by doing experiments on both small scale flumes as well as large scale flood channel facility having both smooth and rough flood plains.

Fernands et al. (2012) performed experiments on a symmetric compound channel for two roughness conditions. For the first set of experiments two-flow condition were tested for a relative depth (ratio of flood plain flow depth and main channel flow depth) of approximately equal to 0.15 by making the whole compound channel smooth. Another two flow conditions were experimented on the same symmetrical compound channel by making the flood plain rough by using synthetic grass as the roughness material for a relative depth of 0.3 approximately. They assessed the effect of relative depth and flood plain roughens on lateral stream wise velocity distribution and Reynold's stress in the horizontal plane. They observed that the resistance to the flow was increased due the presence of synthetic grass on the flood plain. The velocity gradient was also increased as the flood plain was covered by synthetic grass, which intern increased the Reynold's shear stresses. Evaluation of the accuracy of several discharge prediction methods were presented.

Khatua et al. (2012) derived an improved equation to estimate the boundary shear stress distribution for straight, smooth compound channel up to width ratio 6.67 and relative depth up to 0.5. By balancing the magnitude of shear force at the interface of main channel and flood plain, they made suitable adjustment to the main channel and flood plain wetted perimeters. A modified method was proposed by them to estimate the conveyance of two-stage channels. This method is called as modified divided channel method (MDCM). The method gave good results for both small scale and large scale experimental channels. The results from this method was also found to be similar with results of CES (Conveyance Estimation System). They applied their method to two natural rivers and found that the proposed model gave satisfactory results.

Khatib et al (2013) conducted experiments on asymmetric compound channel for both smooth and rough flumes for overbank flow. Nine new test models were fabricated with changeable main channel width and depth of main channel for mean velocity distribution between main channel and floodplain. The variations and interaction of the mean velocity was probed with respect to relative depth. Single regression equation was modelled for calculating the mean velocity using relative depth as a predictor variable. Again, multiple regression equations were developed by two auxiliary dimensionless variables. Validation was done with different data sets and the prediction of mean velocities used for estimation of flow rate using continuity equation.

Mohanty et al. (2013) conducted experiments in a straight smooth compound trapezoidal main channel with two symmetrical flood plains having a width ratio equal to 12 to evaluate the kinetic energy correction factor and momentum correction factor under varying flow conditions. By measuring the point velocities for the whole two-stage channel, analysis of isovel patterns were performed and magnitudes of energy and momentum correction coefficients were estimated. The Froude number for whole experimental procedure was kept between 0.277 to 0.444 and relative depth between 0.11 to 0.43. They found the values of energy coefficient and momentum coefficient as 2.09 and 1.39 respectively. They also suggested new equations to determine the approximate values of these correction factors.

Khatib and Gogus (2014) studied the flow structures of asymmetric compound channel by taking nine models of rectangular asymmetric compound cross-section. The flow depths and corresponding conveyances were assessed for each model. From these results, average discharges were determined using Φ-indices method. Five dimensionless variables were used to develop a multi variable regression model to estimate the discharge capacity of the experimental channels. The discharges resulted from the Φ-indices method were compared with the observed discharges. They concluded that almost all the tested methods predict discharge with acceptable accuracy at lower relative depth ratios.

Devi and Khatua (2016) performed experiments to quantify the shear layer width and to obtain new calibrating coefficients for secondary flow and friction factor. After getting the calibrating coefficients, these coefficients were modelled for main channel, flood plain and shear layer regions. They also found that numerical approaches like SKM provided good results of depth averaged velocity distribution, but failed miserably in shear layer regions as maximum energy was consumed in the shear layer region due to the high intensity of turbulence and mixing of water. Another finding from their research was that the shear layer width depends on the mean velocities of main channel and flood plain, whereas the friction factor in the shear layer region depends on the nom-dimensional lateral distance and relative depth. A new division was proposed for application of RANS to a compound channel flow, which was based on the mixing layer width. According to the researchers, a compound channel can be divided into four sub-sections; main channel, main channel shear layer, flood plain shear layer and flood plain. When the new calibrating coefficients and the new divisions were tested against other experimental sets, FCFC data and natural river data sets, they found satisfactory results.

2.3 Research Gap

1. Much literatures were found in smooth compound open flows. However, a limited literature exists in rough compound channel.
2. A vast investigation was found in symmetric compound channels however, a little research was investigated in asymmetric compound channels.
3. Many researchers gave models and equations to nullify the errors in predicting discharge capacity of a compound channel with homogenous roughness. However, for non-homogenous compound channels, the output indicated a significant variation in discharge from the observed values.
4. A very less literatures were found on variation of energy and momentum correction factors on asymmetric compound channels. Therefore, the present study involves the experimentations in rough compound channels with asymmetrical flood plains. Further improved expressions are given for estimating flow parameters for both symmetric and asymmetric compound channels.

Chapter- 3

EXPERIMENTAL SETUP AND PROCEDURES

3.1 General

In order to assess the impact of differential roughness of main channel and flood plain on flow characteristics like depth-averaged velocity, flow distribution, boundary shear stress distribution, variation in overall and zonal Manning's *n* and discharge during over bank flow condition in a two-stage channel, experiments were carried out at the Fluid Mechanics and Hydraulics Laboratory of the Civil Engineering Department, National Institute of Technology, Rourkela, India. Two sets of experiments were conducted in an asymmetrical compound channel. In both cases, the flood plain was roughened with respect to the main channel. In this section, the whole experimental set up was described with some photographs.

3.2 Fabrication of Experimental Flume

A straight asymmetrical compound channel was used for the present study, which was fabricated inside a tilting flume of dimension 12m long, 2m wide and 0.6m deep. The tilting flume was made up of mild steel bars and plates. A large reinforced cement concrete (R.C.C) tank was constructed at the upstream side of the flume to supply water into the experimental channel. A volumetric tank is situated at the downstream side of the channel to measure the discharge for each flow depth. Three centrifugal pumps of 10 HP capacity were used for the experimental procedure having suction pipes installed inside a large underground sump located outside the laboratory and the delivery pipes are connected to the overhead tank. The water discharged from the volumetric tank at the downstream side of the flume again goes back to the underground sump, thus completing the recirculating system. To reduce the turbulence and energy dissipation purpose a stilling chamber fitted with an adjustable head gate and a series of baffle walls was provided at the beginning of the flume. To make the flow uniform over the channel and minimum head loss at the inlet section, a bell mouth entrance to the experimental channel was provided. In addition, an adjustable tailgate was there at the downstream of the flume to maintain the uniformity of flow.

Fig 3.1: Photo of three 10 HP pumps

Fig 3.2: Photo of overhead tank

Fig 3.3: Photo of inlet with baffle walls

Fig 3.4: Photo of volumetric tank and vertical piezometer

Fig 3.5: Photo of Flow Straighteners with Bell Mouth Entrance

3.3 Experimental Compound Channel

The asymmetric compound channel used for investigation in this study comprised of a trapezoidal main channel having bottom width (b) of 33cm and depth (h) of 11cm with side slope 1:1 which gave a top width of main channel as 55cm and a flood plain at the right side of the main channel (when looking from the upstream side) of width 63.8cm and depth 14cm with 1:1 side slope.

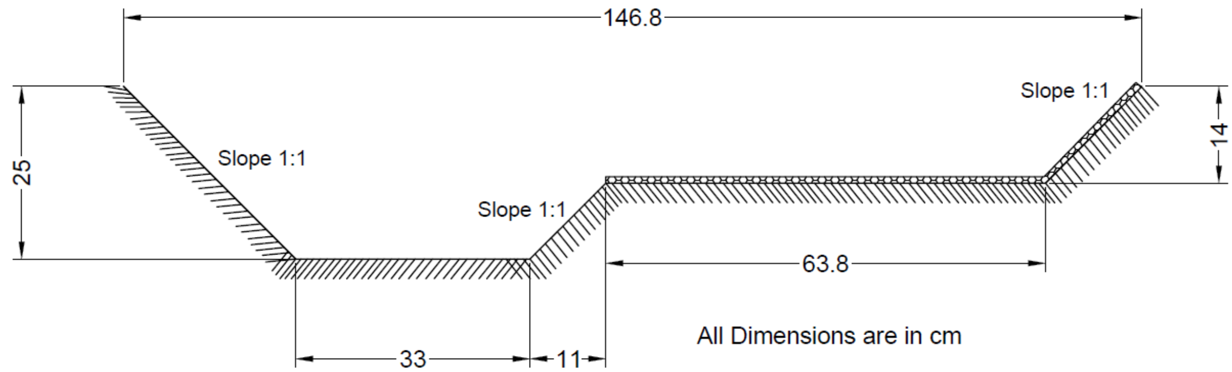


Fig 3.6: Cross-section of the rough asymmetric compound channel

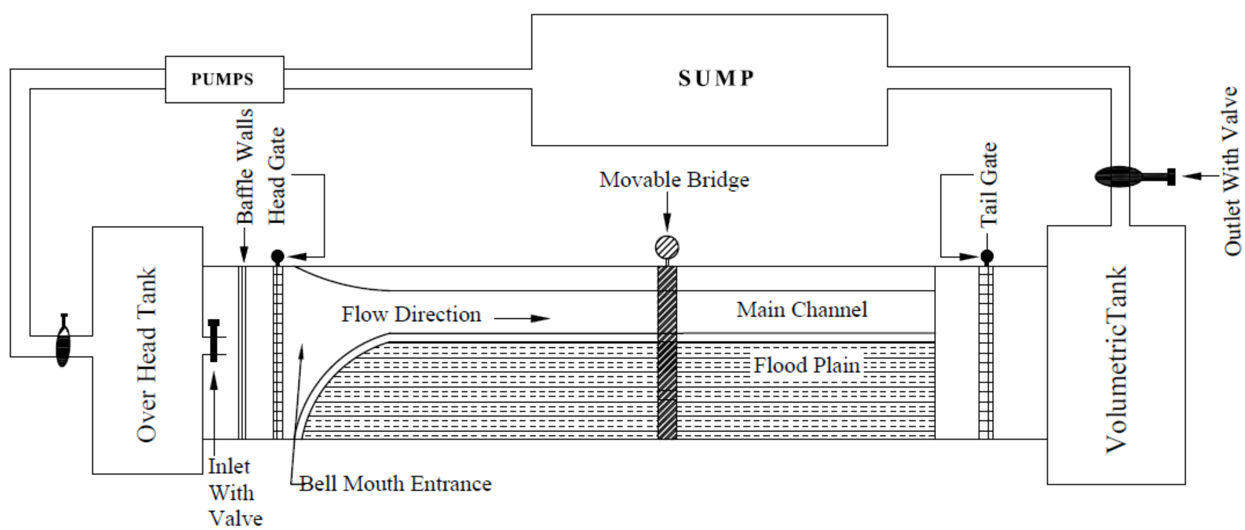


Fig 3.7: Plan view of the asymmetrical compound channel having plastic mat on flood plain

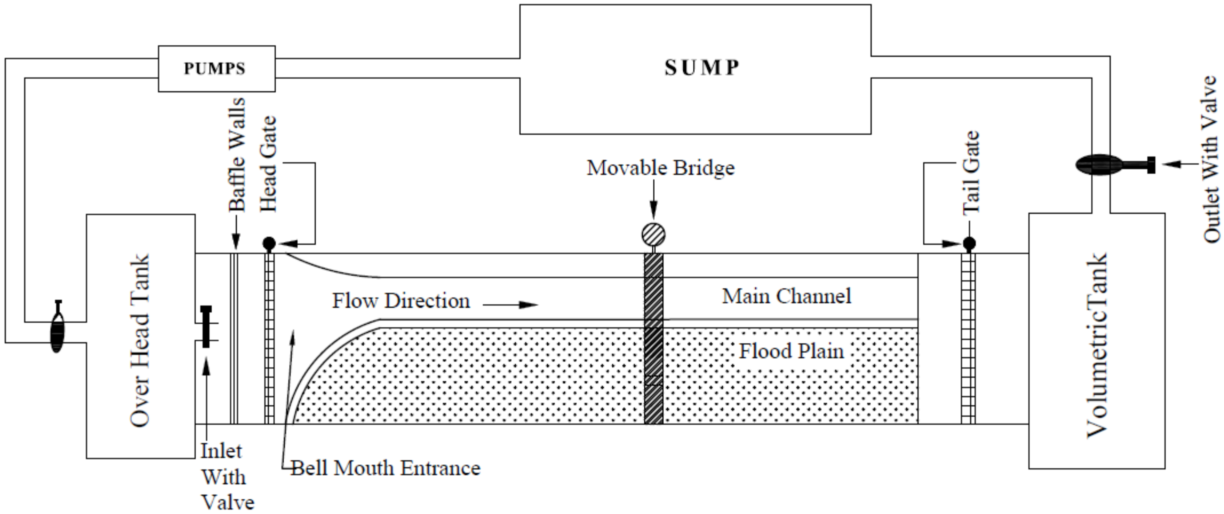


Fig 3.8: Plan view of the asymmetrical compound channel having small gravel on flood plain

Experiments were conducted on the asymmetric compound channel for two different flood plain roughness conditions. In the first set of experiments the main channel was remained smooth having cement concrete trowel finish of Manning's (*n*) value 0.01 whereas the flood plain was made rough by gluing commercially available plastic mat on it of thickness 15mm having Manning's (*n*) value 0.024. For the second set of experiments, the roughness condition of main channel was remained constant but the roughness condition of flood plain was changed to small gravel from plastic mat with a Manning's (*n*) value 0.02.

Fig 3.9: Photo of both types of roughness material used on flood plain

For the measurement of water depth, a point gauge was used along the centreline of the main channel of the compound channel. The bottom of main channel was taken as datum line for water depth measurement in the asymmetric compound channel. Volumetric discharge measurement was done using a vertical single tube manometer, which was fitted to the volumetric tank by measuring the rise of water with time. To get the discharge for a particular flow depth, the plan area of the volumetric tank was multiplied with height of 1cm water in the vertical single tube manometer and then this multiplication was divided by average time taken for 1cm rise.

Table 3.1. Detailed Geometrical Features of The Experimental Channel

Sl No.	Item Description	Experimental Channel
1	Channel Type	Straight
2	Geometry of main channel	Trapezoidal (Side slope 1:1)
3	Geometry of flood plain	Trapezoidal (Side slope 1:1)
4	Flood plain type	Asymmetric
5	Main channel base width (b)	0.33m
6	Depth of main channel (h)	0.11m
7	Flood plain base width (b_f)	0.638m
8	Width of compound channel at flood plain bed level (B)	1.188m
9	Bed slope of the channel(S_0)	0.001
10	Width Ratio ($\alpha=B/b$)	3.6
11	Aspect Ratio ($\delta=b/h$)	3

3.4 Experimental Procedure

This section involves some important steps involving the successful measurement of velocity, discharge and other findings using some advanced instruments. The first condition to do the experiment was to maintain the flow subcritical (i.e. Froude No. (F_r) < 1). To maintain the flow subcritical a mild slope of value 0.001 was given to the flume. Due to which the flow of water within the asymmetric compound channel was under gravity. Different methods could be adopted to maintain the desired slope for the flume. For the recent study, two methods were used to obtain the required bed slope of the channel. The following methods were followed for the first method. A certain depth of water was maintained in the main channel by closing the tailgate. By fixing two end points of length 6m, water heights at the two positions were noted with the help of a point gauge with0.1mm least count. The point gauge was fitted to a travelling bridge so that it could move in transverse as well as in longitudinal direction of the compound channel. Then the difference in heights of water at the two ends fixed before was divided by the reach length to obtain the slope. The bed slope obtained from this method was 0.001 for the asymmetrical compound channel. The second method was quite easier than the first method. A certain depth was maintained in the main channel and a pipe filled with water was laid above the water level on the main channel up to a certain length. The two ends of the pipe were fixed. Then the piezometric head difference between the two ends was recorded. Then this piezometric head difference was divided by the length of the pipe to get the bed slope. In this case, the bed slope was found to be nearly equal to the first method.

3.4.1 Determination of base *n* value for different surface material

Generally, a flow in a channel experiences resistance due to the roughness of material present on the channel bed. To express this roughness, Manning's roughness coefficient (*n*) is used. Therefore, the evaluation of actual flow capacity of channel depends on accurately calculated value of roughness coefficient. In the present work, an asymmetrical compound channel was used for experimentation in which the main channel was smoothened by cement concrete trowel finished surface. However, two types of roughening materials were used for flood plain. For first case plastic mat (rough type-1), and for second case small gravels (rough type-2) were used on the bed of flood plain. To obtain the Manning's *n* value for each material, in bank flow experiments were conducted for each type of material. Then discharge and wetted area for each experiment were noted from which the mean velocity was calculated. Then Manning's formula was applied by using this mean velocity to get the base *n* value for each material.

$$n = \frac{1}{U_m} R^{2/3} S_0^{1/2} \tag{3.1}$$

Where U_m is the mean velocity, R is the hydraulic radius (A/P), A is the wetted cross-sectional area of flow, P is the wetted perimeter of the cross-section, and S_0 is the bed slope of the channel.

3.4.2 Measurement of depth of water and discharge

Some limitations were always associated with the experimental process, without which the experiments could not be executed properly. One of the important limitation for the whole experimental procedure was to make the flow uniform and laminar. To achieve this condition, the flow of water was made to pass through a stilling chamber inside which a series of baffle walls and flow straighteners were there, so that the turbulence in flow could be reduced and the uniformity in the flow might be maintained throughout the channel. In addition, the flow of water was allowed to run for a sufficient time (about 4 to 5 hours). Then along the centreline of the main channel, a point gauge was used to record the flow depth.

The following procedures were taken to measure the respective discharges for each flow depth. A vertical single tube piezometer was fitted to the volumetric tank. The outlet valve to the underground sump was closed to allow the water rise inside the volumetric tank and also in the piezometer fitted to it. When the rise of water inside the piezometer was constant, the time taken to rise 1cm of depth was recorded with the help of a stopwatch for 15 to 20 times. Then the multiplication of volumetric tank area and 1cm rise in the piezometer was divided by the average of the recorded times to get the discharge for the respective flow depth.

The details of hydraulic parameters for the asymetric compound channel are given in the table 3.2

Table 3.2: Details of hydraulic parameters for the asymetric compound channel

Material		Flow Depth, H (m)	Area of Flow A, (m^2)	Wetted Perimeter, P (m)	Discharge, Q (m^3/s)	Mean Velocity, U_m (m/s)	Bed Slope, S_o
Main Channel	Flood Plain						
Cement Concrete Trowel Finish (n=0.01)	Plastic Mat (n=0.024)	0.134	0.077536	1.34901	0.03400	0.43852	0.001
		0.14	0.085	1.36598	0.03704	0.43573	0.001
		0.147	0.093799	1.38578	0.04050	0.43181	0.001
		0.1545	0.103335	1.40699	0.05030	0.48677	0.001
		0.16	0.1104	1.42255	0.05400	0.48916	0.001
		0.165	0.116875	1.43669	0.05961	0.51002	0.001
Cement Concrete Trowel Finish (n=0.01)	Small Gravel @size 7-20mm (n=0.020)	0.14	0.079672	1.35467	0.04027	0.50536	0.001
		0.145	0.085907	1.36881	0.04323	0.50326	0.001
		0.156	0.0998	1.39992	0.05439	0.54504	0.001
		0.16	0.104912	1.41123	0.06074	0.57899	0.001
		0.17	0.117832	1.43952	0.06905	0.58607	0.001
		0.176	0.12568	1.45649	0.07712	0.61365	0.001
		0.181	0.132275	1.47063	0.08202	0.62007	0.001

3.4.3 Measurement of Velocity

For the measurement of velocity a micro ADV (Acoustic Doppler Velocimeter) and a Pitot tube was used. The micro ADV was used for the main channel velocity data acquisition and the Pitot tube was used on flood plain for measuring velocity of flow. The ADV can measure three-dimensional velocity whereas the Pitot tube is only able to measure the one dimensional velocity (velocity along the flow direction).

3.4.3.1 Micro ADV (Acoustic Doppler Velocimeter)

For the present experimental work, a 16- MHz micro ADV was used which was provided by M/sSon-Tek, SanDiego, USA. For laboratory study, the micro ADV is a very efficient instrument due to the higher acoustical frequency (16- MHz). Doppler shift principle is used by the Micro-ADV to measure the velocity of small particles by assuming that the particles are moving with the same velocity as the fluid. The ADV has lot off advantages. It can record 3-D velocity field. The sampling rate is very high i.e. up to 50Hz. Sampling volume is less than $0.1cm^3$. The range of magnitude of velocity acquisition is very wide (1mm/s to 2.5m/s). It can also perform excellent under low flow conditions. There is no need of recalibration.

The sampling volume was set to be $0.09cm^3$ and located at a distance of 5cm below the probe tip approximately. To get a better quality of data by using ADV, some conditions should be met. The correlation should be in the range 70 to 100%. However, for mean velocity measurements the correlation value can be as low as 30%. For 16-MHz micro ADV, the signal to noise ratio (SNR) should be more than 20dB. The manufacturer of this ADV, Son-Tek recommended a value of SNR as more than about 30dB for higher sampling rate (e.g. 50Hz). Despite of having a number of advantages, it has a limitation. The ADV used for this experiment cannot measure velocity for flow depths below 5cm.

3.4.3.2 Micro-ADV used in Experimental Work

A test section was chosen at a distance of 8m from the bell mouth entrance for data collection purpose. At this test section the ADV was placed and the three directional velocities were recorded in longitudinal direction that along the flow direction, in lateral direction and in vertical direction. Two types of Micro-ADVs were used in this experiment, a down probe and an up probe. In down probe, the probe tips are in downward direction and in up probe, the probe tips are in upward direction. Due to the limitation of Micro-ADV, the down probe could not collect the velocity data of upper 5cm of flow depth. In this case, the up probe was used to measure the velocity. Here the ADV was used only on main channel. The ADV could not be used on the flood plain, as the depth flow on the flood plain was less than 5cm for the first set of experiments. However, for second set of experiments where the flow depth was higher (*H=17cm, 17.6cm and 18.1cm*), ADV was used on the flood plain also. The cases where ADV could not be used, a Pitot tube was helpful to measure the velocity but only along the flow direction i.e. only 1-D velocity.

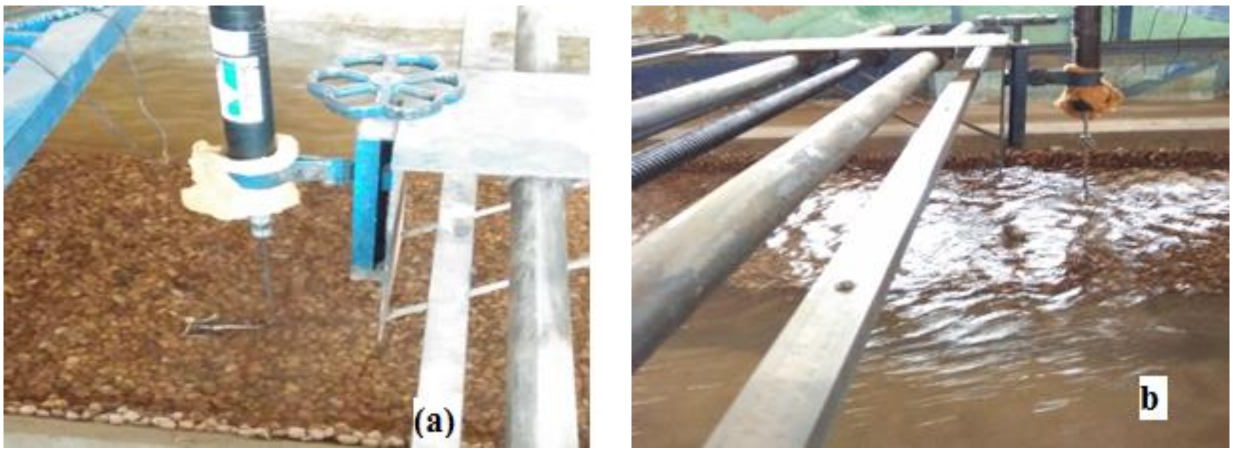


Fig 3.10: Photos of Different Types of ADV (a) Up probe (b) Down probe

3.4.3.3 Measurement of velocity using Pitot tube

To measure the velocity of flow of water on flood plain where the Micro-ADV could not be used, a micro Pitot tube of external diameter 4.77mm connected to an inclined manometer was used. The Pitot was made fixed to a main scale having Vernier scale of least count 0.1mm. To get the total pressure value, the main hole of the Pitot tube was kept normal to the flow direction and the surface holes gave the static pressure. These two pressures were in form of water heights in the tubes of inclined manometer. Then the head difference between the two limbs of the inclined manometer was noted. Then from Bernoulli's equation using this head difference (Δh), velocity (U) of that particular point where the Pitot tube was there was calculated.

$$U = \sqrt{2g\Delta h sin\theta} \quad (3.2)$$

Where g the acceleration due to gravity and θ is is the inclination angle of the manometer to the horizontal base. For the first and second set of experiments, the inclinations were 33.57^0 and 38.2^0 respectively.

Fig 3.11: Photo Showing Pointer Gauge and Pitot Tube

3.4.4 Measurement of Boundary Shear Stress

It is very important to measure the boundary shear stress for any type of channel as it plays an important role in sediment transport and erosion of the channel bed as well as the sidewalls. The Pitot tube which was used for velocity measurement across the flood plain, the same Pitot tube was used for measurement of boundary shear stress (τ_b) throughout the wetted perimeter of the asymmetric compound channel used in this experimental process. Same procedure was adopted that was adopted in velocity measurement using Pitot tube. But the computation method was different. To compute the boundary shear stress, Patel's calibration method (Patel, 1965) for Preston tubes was used. Patel (1965) suggested that the point boundary shear stress over the solid boundary could be measured indirectly by knowing the difference in static and dynamic pressure values (Δp) observed in the static and dynamic hole of the Pitot tube respectively with an accuracy of$\pm 6\%$. The various relationships, which were suggested by Patel given as follows.

$$y^* = 0.50x^* + 0.037, \qquad 0 \le y^* < 1.50 \quad \text{Or} \quad 0 \le x^* \le 2.9 \tag{3.3}$$

$$y^* = -0.0060x^{*3} + 0.1437x^{*2} - 0.1381x^* + 0.8287, \qquad 1.50 < y^* < 3.50 \quad \text{Or} \quad 2.9 \le x^* \le 5.6 \tag{3.4}$$

And

$$x^* = y^* + 2\log_{10}(1.95y^* + 4.02), \qquad 3.50 < y^* < 5.30 \quad \text{Or} \quad 5.6 \le x^* \le 7.6 \tag{3.5}$$

With $$x^* = \log_{10}\left(\frac{(\Delta p)d^2}{4\rho\vartheta^2}\right)$$ (3.6)

And $$y^* = \log_{10}\left(\frac{\tau d^2}{4\rho\vartheta^2}\right) \quad (3.7)$$

Where, d and ϑ represent external diameter of the Pitot tube and kinematic viscosity of the liquid respectively. After knowing the range of x^* values an appropriate was chosen to evaluate the boundary shear stress. After getting the point boundary shear stress values, these were integrated across the entire wetted perimeter to get the total shear force per unit length normal to the flow cross-section. After getting the total shear force from experiment, it was compared with the shear force value by energy gradient method to check the accuracy of the experimental values. The comparison is given in Table 3.3 and the error percentages are observed within the limit of $\pm$10%

Table 3.3: Comparison of calculated shear force with energy gradient approach

Channel	Relative Depth (D_r)	Total Shear Force from Energy Gradient Method (N/m)	Total Shear Force from Preston Tube Measurement (N/m)
Roughness-1	0.1791	0.7606	0.6921
	0.2143	0.8339	0.7524
	0.2517	0.9202	0.8290
	0.2880	1.0137	0.9136
	0.3125	1.0830	0.9785
	0.3333	1.1465	1.0489
Roughness-2	0.2143	0.7816	0.7043
	0.2414	0.8427	0.7848
	0.2949	0.9790	0.8838
	0.3125	1.0292	0.9389
	0.3529	1.1559	1.0515
	0.3750	1.2329	1.1459
	0.3923	1.2976	1.1938

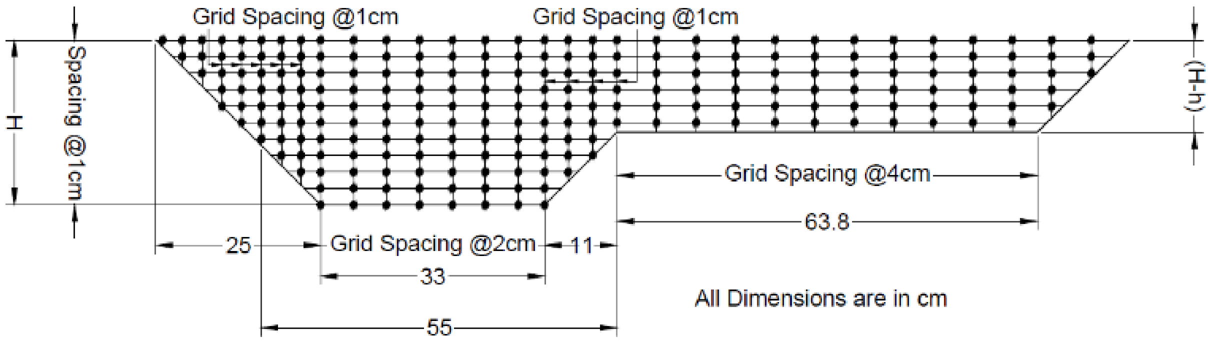


Fig 3.12: Grid points for measuring the velocity and boundary shear stress in asymmetrical compound channel

Chapter-4

RESULTS AND DISCUSSIONS

4.1 General

This section represents all the results covering stage-discharge curves, depth averaged velocities, boundary shear stress etc. from the new experiments which were carried out on the asymmetric compound channel of NIT, Rourkela. Two sets of experiments were carried out on a symmetrical compound channel with different roughness properties for main channel and flood plain. The first set of experiments were done using plastic mat as roughness characteristic for flood plain and small gravel as roughness on flood plain for the second set of experiments. So subsequently different subsection are made to deal with the results of the different experiments.

4.2 Stage – Discharge Curve

It is plotted between depths of water on the bed of the main channel to the corresponding discharges. It is also known as rating curve. It is the simplest way of predicting discharge for a channel. But to develop a good rating curve, a large amount of over bank flow data are required. Then a stage discharge curve for that channel can be plotted which will be very helpful to predict discharge without measuring physically. Here the stage discharge curve for the experimental channel is presented in Fig. 4.1. The plot is divided into two parts. Below the bank full line the data represent in bank flow condition and above it over bank flow is there. The in bank flow data are collected from the thesis of Khuntia (2016) as he conducted in bank flow experiments on the same main channel of the present channel.

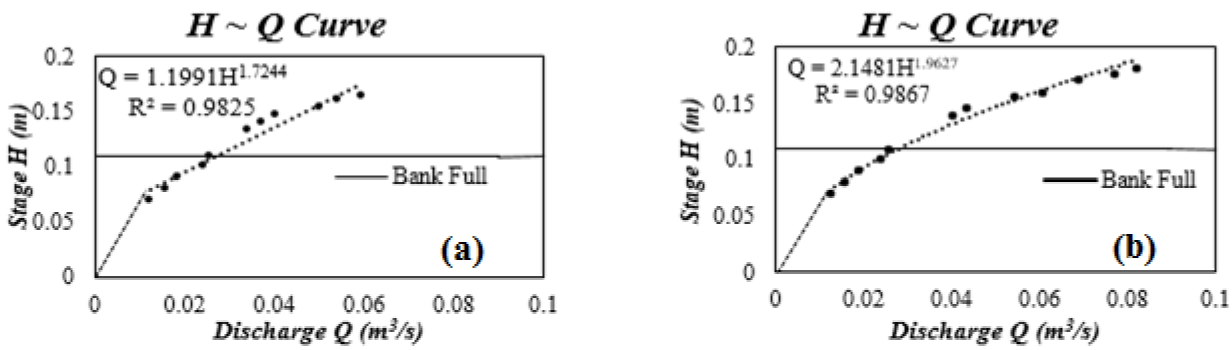


Fig 4.1 Stage – Discharge curve for asymmetric compound channel (a) Roughness-1 (b) Roughness-2.

The properties of the above plots are given in the table below.

Table 4.1: Stage-Discharge Relationships for the asymmetric compound channel

Roughness used on flood plain	Stage-Discharge Relationship	Coefficient of Regression(R^2)
Roughness-1(Plastic Mat)	$Q = 1.1991H^{1.7244}$	$R^2 = 0.9825$
Roughness-2(Small Gravel)	$Q = 2.1481H^{1.9627}$	$R^2 = 0.9867$

4.3 Depth-Averaged Velocity Distributions

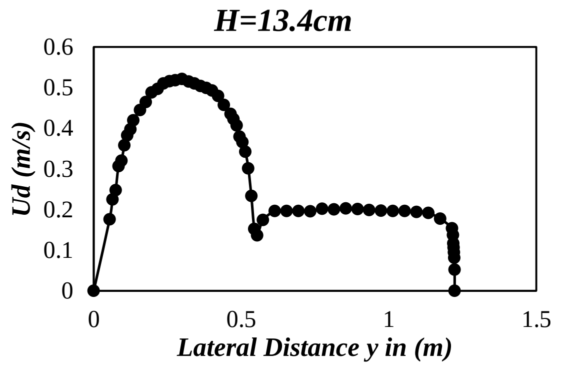
The depth-averaged velocities (U_d) were calculated for all flow depths of asymmetric rough compound channels using the equation 4.1 given below.

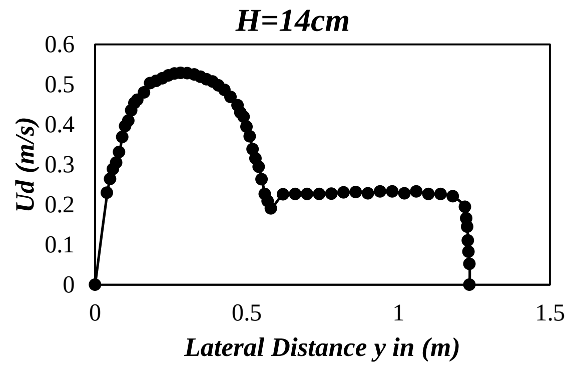
$$U_d = \frac{1}{H}\int_0^H U dz \tag{4.1}$$

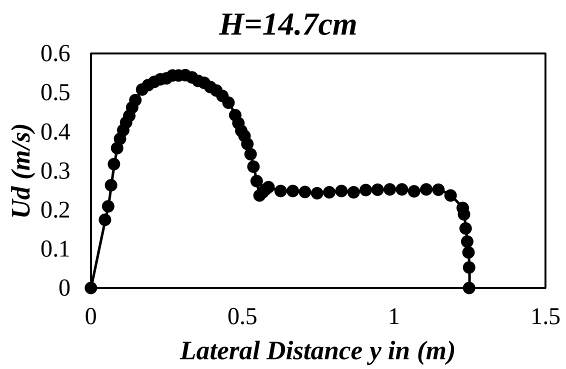
Where U is the point velocity at a vertical line. U_d is calculated by integrating local point stream wise velocities (U) over a flow depth H. Depth averaged velocity distribution is a plot, which is plotted by joining the obtained value of U_d along the lateral direction of a channel.

The results of depth-averaged velocity distributions across the lateral distance of the asymmetric compound channel for both roughness cases are given below.

Roughness-1:


H=13.4cm
Ud (m/s)
Lateral Distance y in (m)


H=14cm
Ud (m/s)
Lateral Distance y in (m)


H=14.7cm
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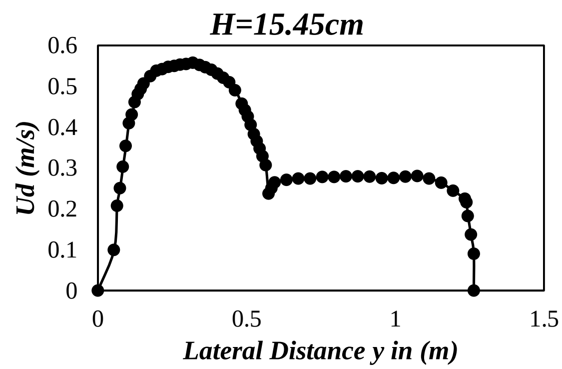
Lateral Distance y in (m)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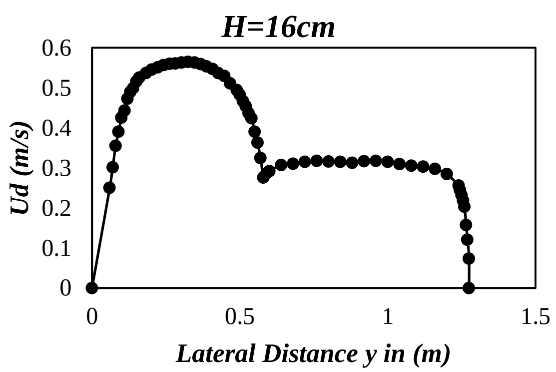
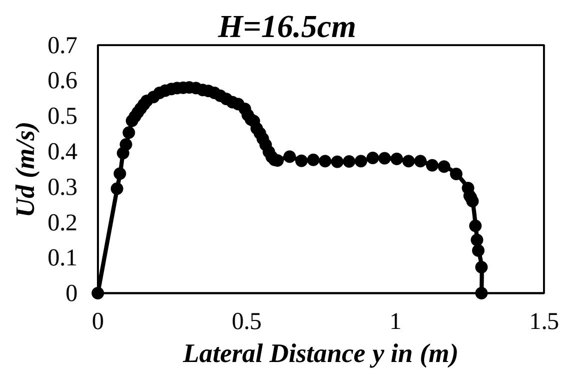
Ud (m/s)
Lateral Distance y in (m)


H=16cm
Ud (m/s)
Lateral Distance y in (m)


H=16.5cm
Ud (m/s)
Lateral Distance y in (m)

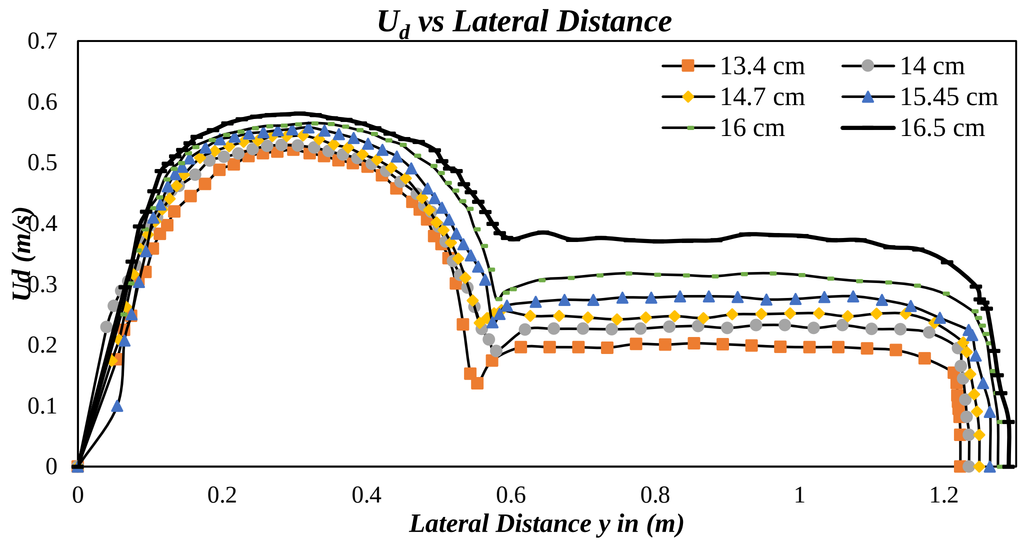
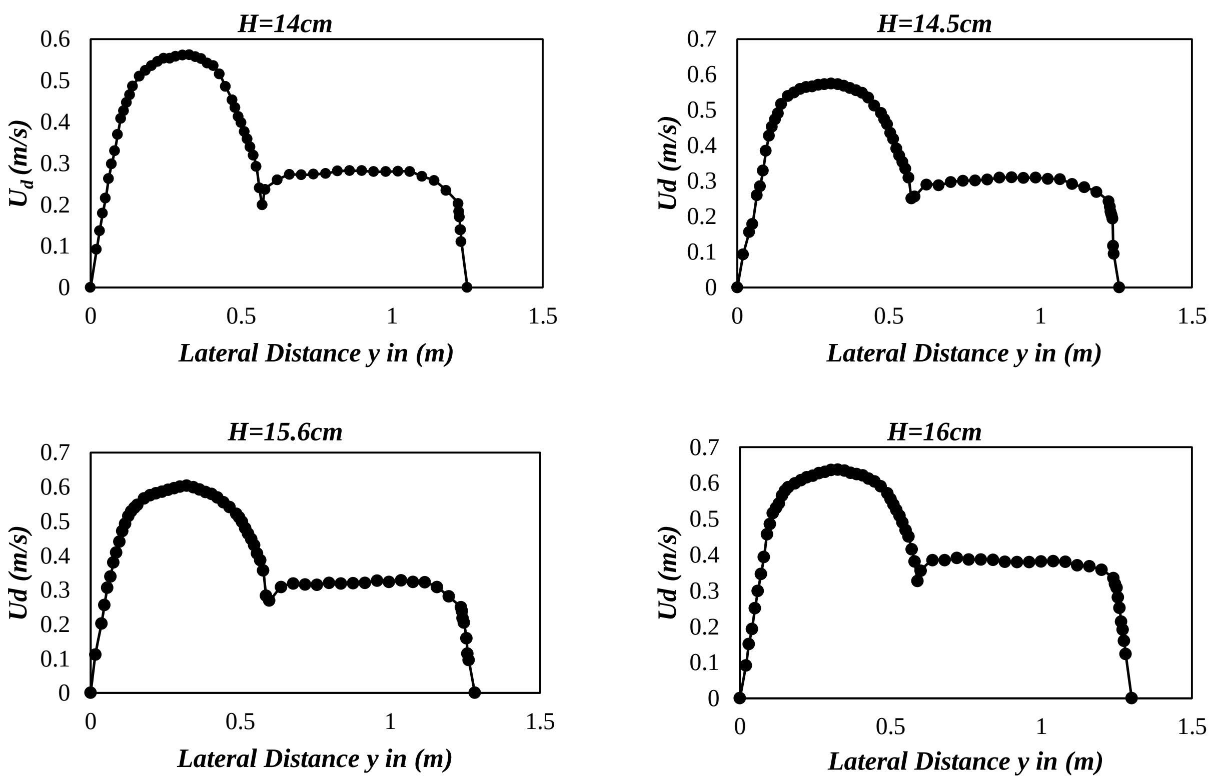
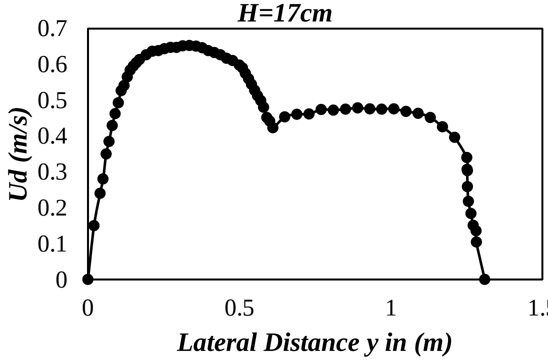
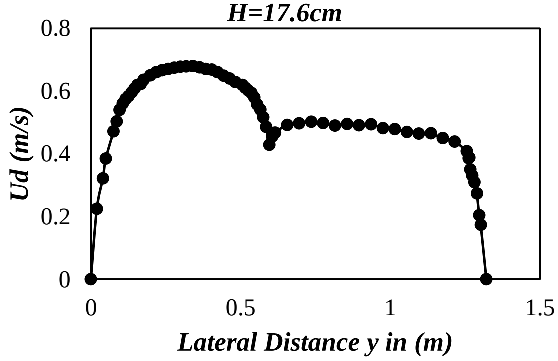


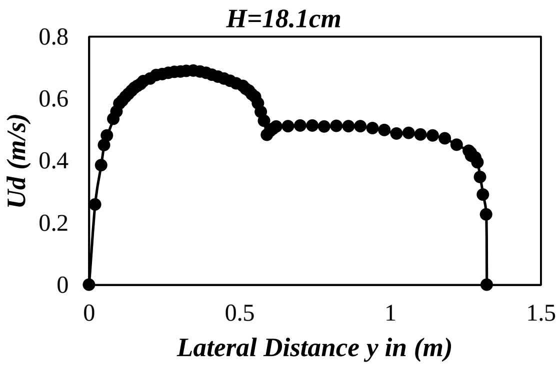
Fig 4.2: Depth-Averaged velocity plots for all depths of Roughness-1.

Roughness-2:









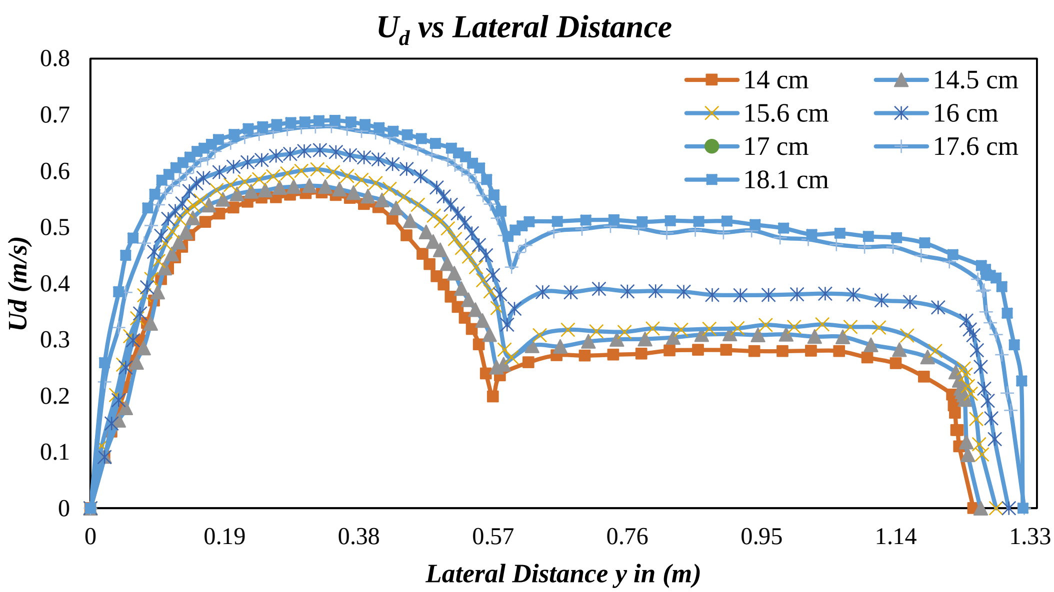


Fig 4.3: Depth-Averaged velocity plots for all depths of Roughness-2

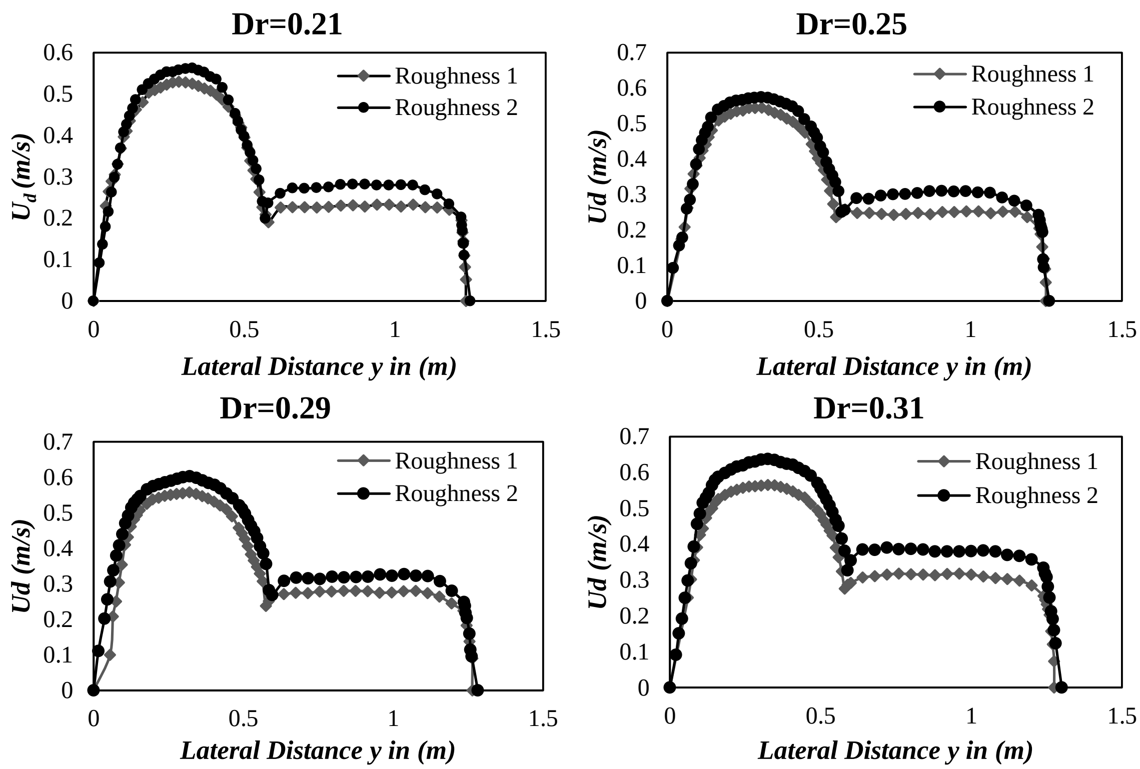


Fig 4.4: Comparisons of Depth-Averaged velocity plots for same relative depth (D_r) cases for both roughness conditions

4.3.1 Discussions

From Figure 4.2 and figure 4.3, it is observed that the U_d increases, as the depth of flow increases. Also one can find that in shallow flow depth cases, the value of U_d at junction of main channel and flood plain fluctuates and become uniform when flow depth rises. It is also observed that for higher over bank flow depths the difference in velocity between main channel and flood plain is less in comparison to shallow flow depth cases. The fluctuation is more for lower flow depths as compared to higher flow depths. As the momentum transfer between main channel and flood plain is more for shallow flow depth cases the fluctuation is seen more. However, when the flow depth rises this momentum transfer decreases and the difference between the hydraulic properties of main channel and flood plain minimizes. This is the reason of less difference between main channel and flood plain velocities for higher flow depth cases.

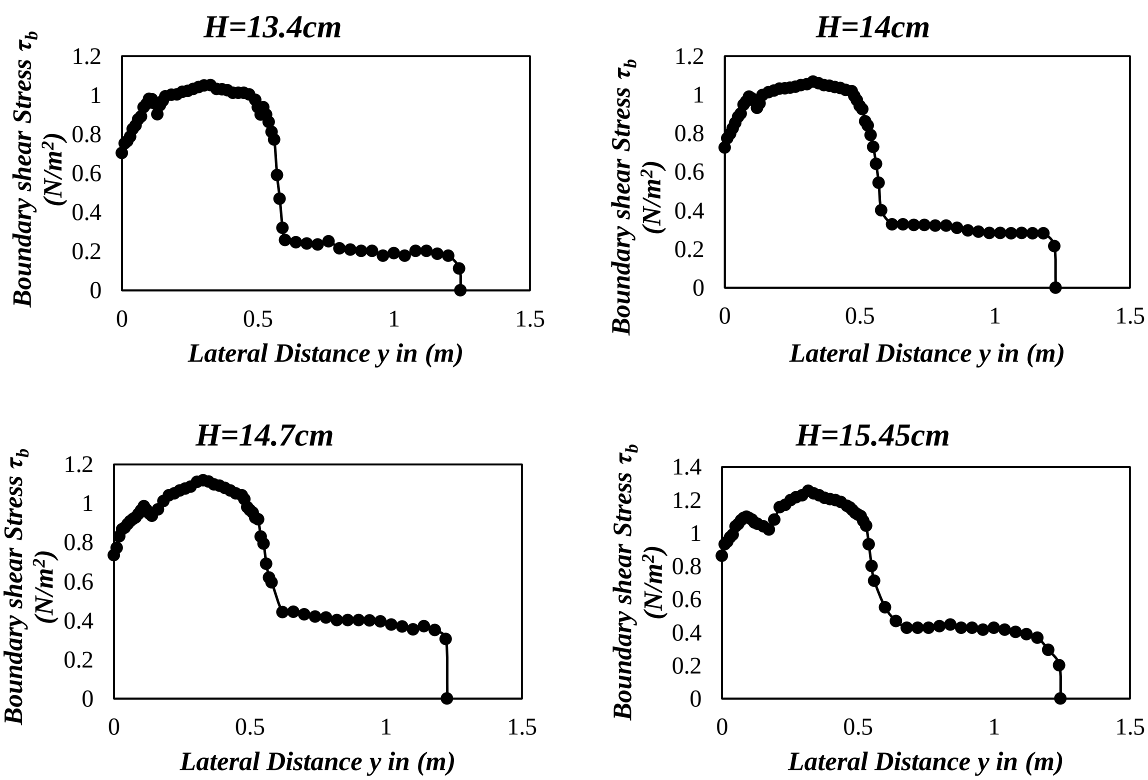
In addition, another property of the depth-averaged velocity plots can be observed that velocity in flood plain is more for roughness-2 when compared to velocity of flood plain of roughness-1 for same flow depth cases. It is due to the higher Manning's *n* value (0.024) of roughness-1 than the roughness-2 (0.02). As the roughness increases, the velocity also decreases.

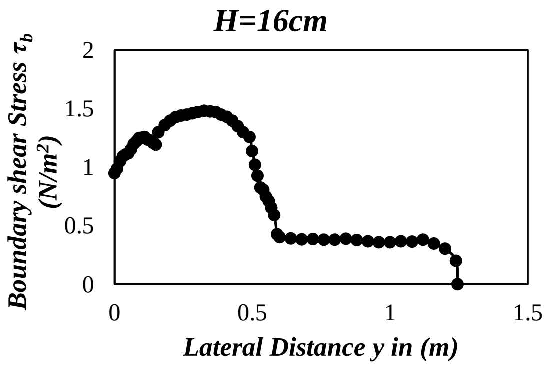
It has been observed that at the left side of the plot, which is the variable flow domain, the velocity is increasing as the flow depth increasing. But in the constant flow domain region of the main channel the velocity is nearly uniform. Again at the right side variable flow domain region of the main channel, the velocity decreases and then increases when going towards the flood plain. Then on the flood plain, again the velocity remains nearly uniform. At the right bank of the flood plain, the velocity decreases.

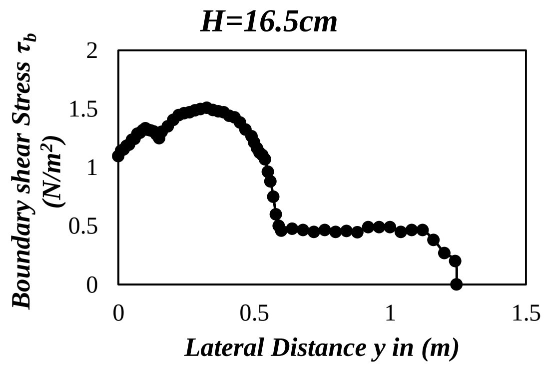
From Figure 4.4, it has been observed that the velocity is increasing when the roughness is decreasing. The Manning's *n* of flood plain roughness material for roughness 1 is 0.024; whereas the Manning's *n* of flood plain roughness material for roughness 2 is 0.02. From Manning's formula we know that the velocity of flow is inversely proportional to Manning's *n*. Therefore, for roughness 2 case the velocity is more than the velocity of roughness 1.

4.4 Boundary Shear Stress

Roughness-1







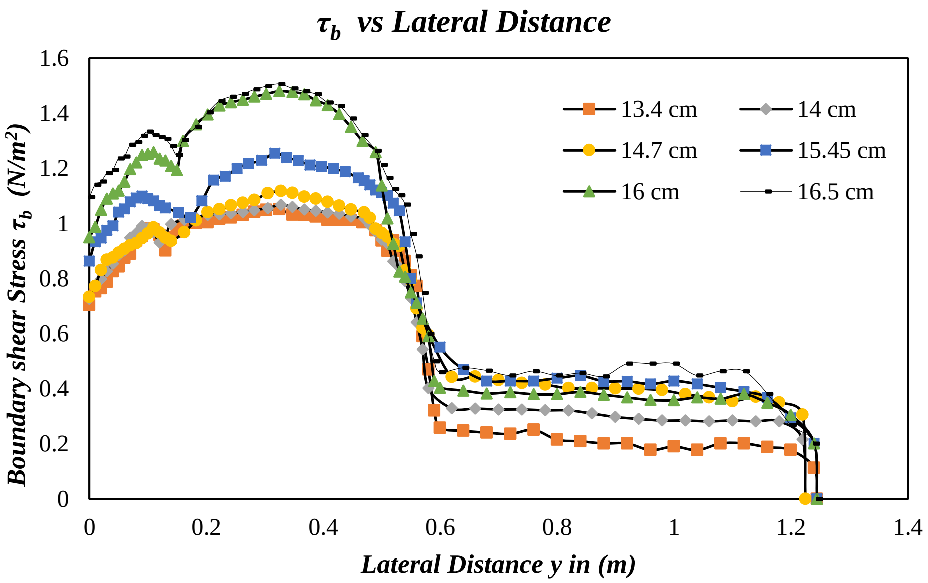
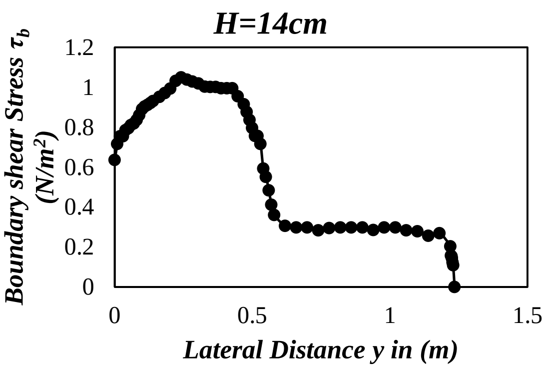
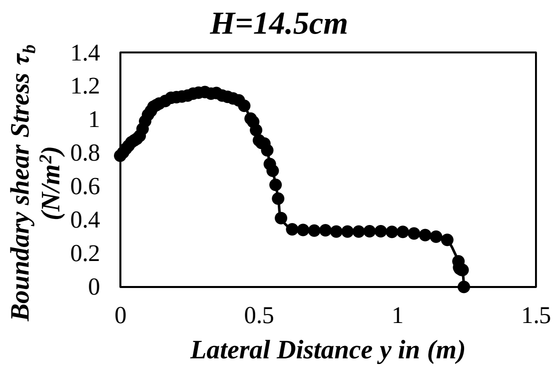
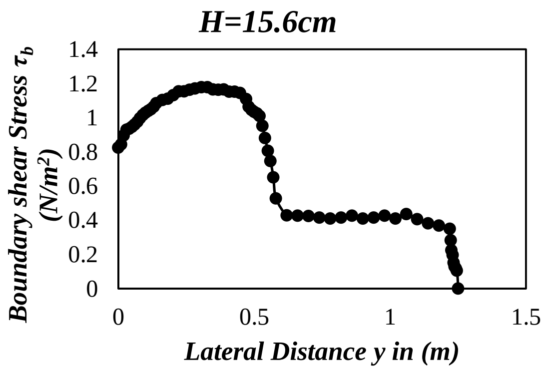


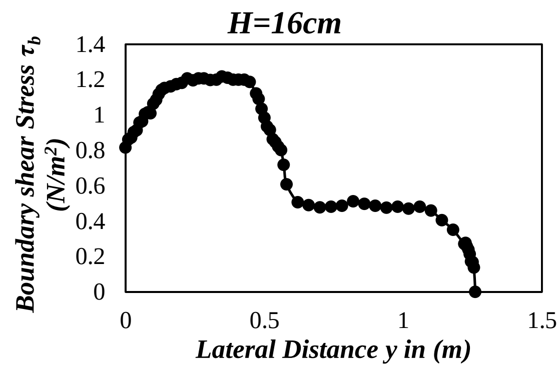
Fig 4.5: Boundary Shear Stress Plots for all depths of Roughness-1

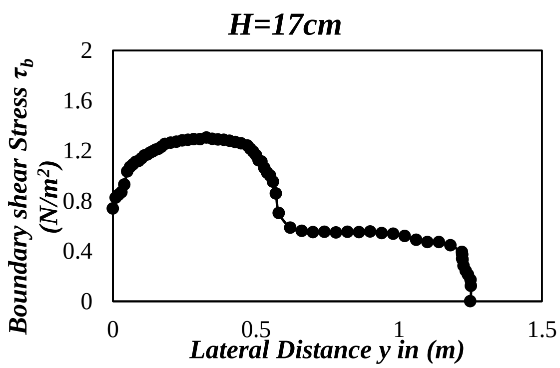
Roughness-2

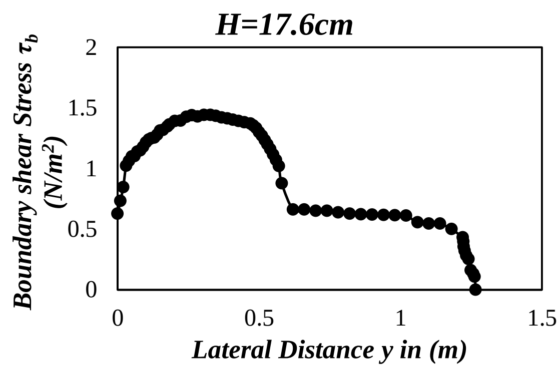


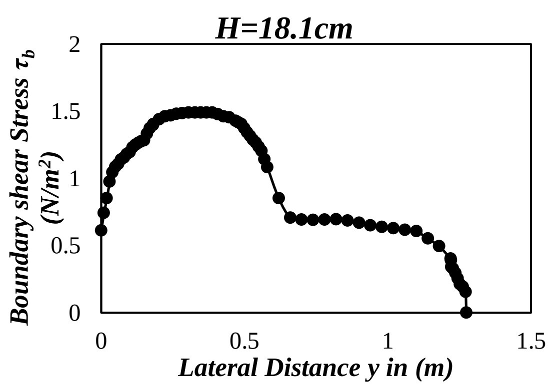



H=15.6cm
Boundary shear Stress τ_b (N/m^2)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
Lateral Distance y in (m)


H=16cm
Boundary shear Stress τ_b (N/m^2)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
Lateral Distance y in (m)


H=17cm
Boundary shear Stress τ_b (N/m^2)
2
1.6
1.2
0.8
0.4
0
0
0.5
1
1.5
Lateral Distance y in (m)


H=17.6cm
Boundary shear Stress τ_b (N/m^2)
2
1.5
1
0.5
0
0
0.5
1
1.5
Lateral Distance y in (m)


H=18.1cm
Boundary shear Stress τ_b (N/m^2)
2
1.5
1
0.5
0
0
0.5
1
1.5
Lateral Distance y in (m)

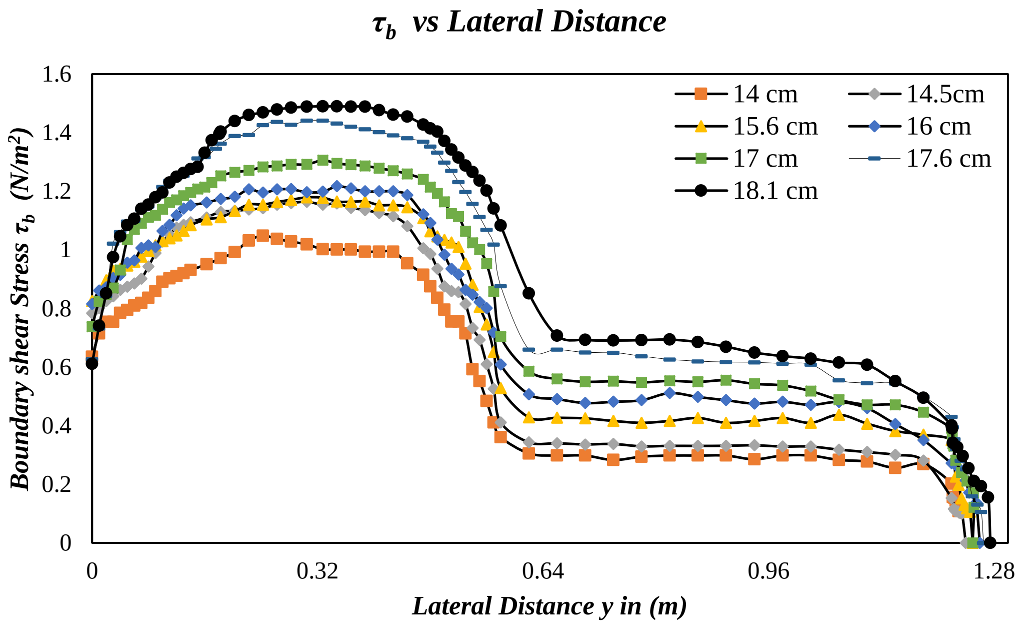


Figure 4.6: Boundary Shear Stress Plots for all depths of Roughness-2

4.4.1 Discussions

From figure 4.5 and 4.6, it has been observed that the boundary shear stress increases with increase in flow depth. The fluctuation of boundary shear stress is more in case of roughness-1 whereas the fluctuation is less for roughness-2 at the junction of variable and constant flow domain of the main channel. The boundary shear stress on flood plain is less than the main channel as the flow depth is more for main channel for both roughness cases.

For higher differential roughness compound channel flow, the boundary shear stress in flood plain is less as compared to the lower differential roughness. For main channel no significant changes are seen as the main channel the roughness is same for both cases. When depth increases, the difference between the boundary shear stress of main channel and flood plain decreases and the gap is more in higher roughness case as compared to lower roughness cases.

Chapter-5

Theoretical Analysis and Discussions

5.1 Energy and Momentum Correction Coefficients

Open channels have a wide range of applications directly or indirectly in our day-to-day life. Open channels are used for irrigation, hydropower, drainage systems etc. Therefore, it is necessary to continuously investigate the open channel flow to achieve a more effective design. So to design an open channel, three basic laws of conservation are applied. These are Law of conservation of mass, Law of conservation of energy and Law of conservation momentum. However, for open channel application, these laws are expressed in terms of continuity equation, energy equation (Bernoulli’s), and momentum equation respectively as shown in equation 5.01, 5.02, 5.03.

Continuity equation

$$Q = A_1U_1 = A_2U_2 = \cdots = A_nU_n \tag{5.01}$$

Energy equation

$$\frac{P_1}{\rho g} + \frac{U_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{U_2^2}{2g} + z_2 + \sum h \tag{5.02}$$

Momentum equation

$$F_r = \rho Q[U_{2x} - U_{1x}] \tag{5.03}$$

Where Q is discharge, A_1, A_2, and U_1, U_2 are cross-sectional area and mean velocity at section 1 and 2 respectively. In all the above three equations, mean velocity is used by assuming steady, uniform flow and non-varying vertically across the flow cross-section. However, for open channels, the velocity distribution is not uniform. The velocity distribution changes along the cross-section due to boundary resistance. So due to the above assumption, the results of energy and momentum may come with an error. While designing open channel structures, the error due to the non-uniform velocity distribution should be corrected. To nullify this error, two correction factors are introduced which are called as energy and momentum correction factor or co-efficient.

To estimate the energy and momentum correction coefficients, equation 5.04 and 5.05 are used and the equations are given below.

$$\alpha_1 = \int_0^A \frac{U^3 dA}{U_m^3 A} \tag{5.04}$$

$$\beta_1 = \int_0^A \frac{U^2 dA}{U_m^2 A} \tag{5.05}$$

Where α_1 is the energy correction factor, β_1 is the momentum correction coefficient, A is total cross-sectional area, U is the velocity of water passing through the small area dA and U_m is the mean velocity of flow. By using the above two equations, energy and momentum correction factors were calculated for the present experimental asymmetric compound channel having two types of roughness on flood plain (Plastic mat- roughness1, small gravel-roughness2) and presented in the table 5.1.

Table 5.1: Energy and momentum correction factors for the experimental channel

Roughness-1			Roughness-2		
H(m)	***α_1***	***β_1***	***H(m)***	***α_1***	***β_1***
0.134	1.235	1.080	0.14	1.189	1.066
0.14	1.180	1.054	0.145	1.173	1.065
0.147	1.169	1.045	0.156	1.141	1.040
0.1545	1.123	1.028	0.16	1.124	1.039
0.16	1.122	1.032	0.17	1.089	1.017
0.165	1.108	1.028	0.176	1.069	1.014
-	-	-	0.181	1.057	1.002

The graphs between energy and momentum correction factors and relative depth for both roughness cases were also plotted and given in figure 5.1 and 5.2.

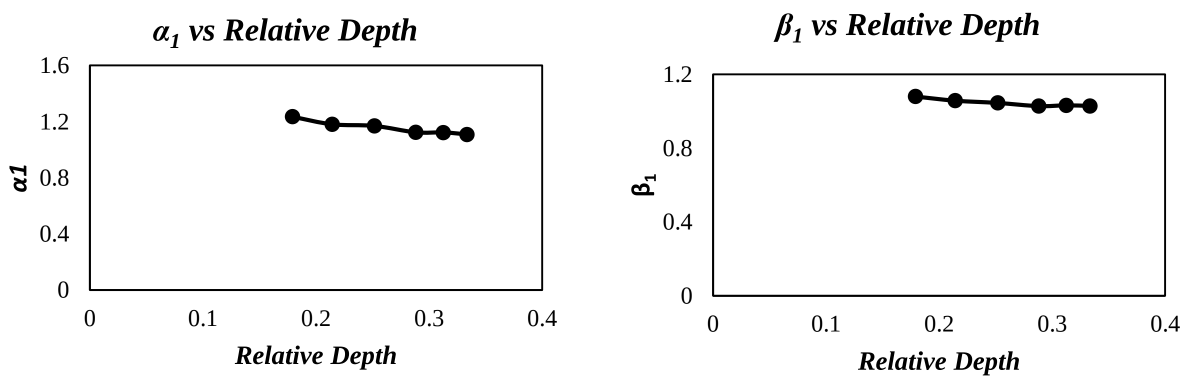


Fig 5.1: Variation of α_1 and β_1 with relative depth for roughness-1

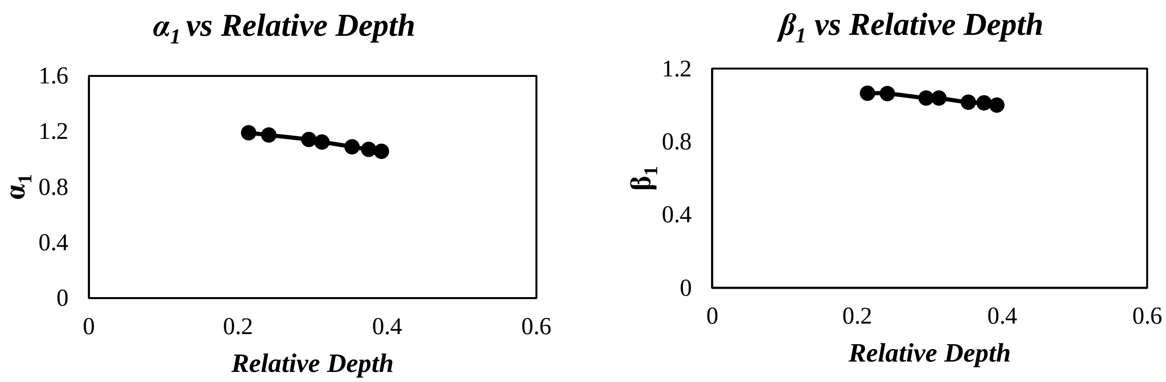


Fig 5.2: Variation of α1 and β1 with relative depth for roughness-2

5.1.1 Observations

From figure 5.1 and 5.2 and table 5.1, it has been observed that the values of energy and momentum correction coefficients decrease with increase in flow depth. In low flow depth conditions, the momentum transfer between slow moving flood plain flow and fast moving main channel flow is intense, whereas when the flow depth increases this momentum transfer decreases as the difference in velocity of flow between main channel and flood plain decreases. Accordingly, the resulted energy and momentum coefficients were higher for low flow depth cases and nearer to one when the flow depth increased for the present experimental channel.

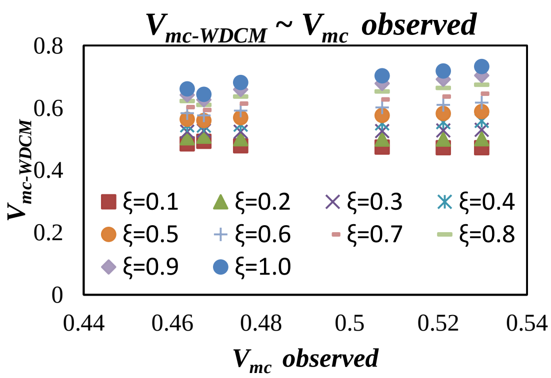
5.2 The Weighted Divided Channel Method

Traditionally compound channels have been analysed by divided channel method by dividing the compound channel into various sub-areas. Generally, vertical or horizontal lines are used to divide the channel. If vertical division lines are used at the edges of main channel, then it is called as vertical division method (VDM) and if horizontal lines are used to separate the channel, then it is called as horizontal division method (HDM). These division lines are made by assuming them as shear free thus not included in weighted perimeter. But according to Myers, due to the turbulent interaction between main channel and flood plain the assumed division lines are not shear free. In most of the cases, the vertical division method over predicts and the horizontal division method under predicts the velocity and discharge of a compound channel. Therefore, to neutralize this under and over prediction, Yen and Overton (1973), Wormleaton and Hadjipanos (1982) proposed inclined division methods. However, a little achievement has been accomplished by these methods. Rather than searching for a perfect location for division lines, a new method was proposed by Lambert and Myers (1998) called as weighted divided channel method, which uses a weighting factor (ξ) to allow a smooth transition between velocity given by vertical division method and velocity predicted by horizontal division method. The value of this weighting factor (ξ) varies from zero to one. The weighting factor is applied to both main channel and flood plain, so that the mean velocity of these areas can be improved. Then to estimate the discharge, these improved new velocities are used. The equation for velocity calculation of main channel is given by equation 5.06.

$$V_{mc-WDCM} = \xi V_{mc-VDM} + (1-\xi)V_{mc-HDM} \quad (5.06)$$

Where $V_{mc-WDCM}$ is the improved main channel velocity, V_{mc-VDM} is the mean velocity predicted by vertical division method, V_{mc-HDM} is the mean velocity given by horizontal division method in the main channel region. A similar equation can be used for flood plain area but the sub-script *mc* should be replaced by *fp*. The weighting factor ξ may or may not be equal for main channel and flood plain. The weighted divided channel method was applied to the present experimental channel for both type of roughness on flood plain (roughness-1, roughness-2). By using trial and error method, the value for weighting factor (ξ) from zero to one was substituted in equation 5.06 to get the mean velocity of main channel and the same equation was used for flood plain also just by replacing the subscript *mc* by *fp*. Then a graph of V_{WDCM} versus observed mean velocity for both main channel and flood plain was plotted for each of the trial ξ value. Among all the plots, the plot, which gives best coefficient of regression (R^2) value, that value of weighting factor, was chosen. All the plots for roughness-1 and roughness-2 is given in figure 5.3 and 5.4 respectively.

Roughnes-1



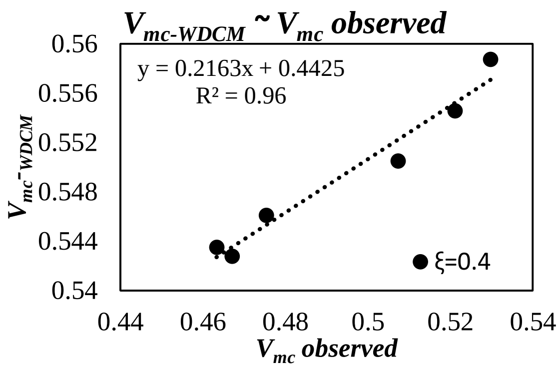


Fig 5.3(a) $V_{mc-WDCM}$ ~ V_{mc} *observed* plot for ξ=0 to 1 and for ξ=0.4 with maximum R^2 for Roughness-1

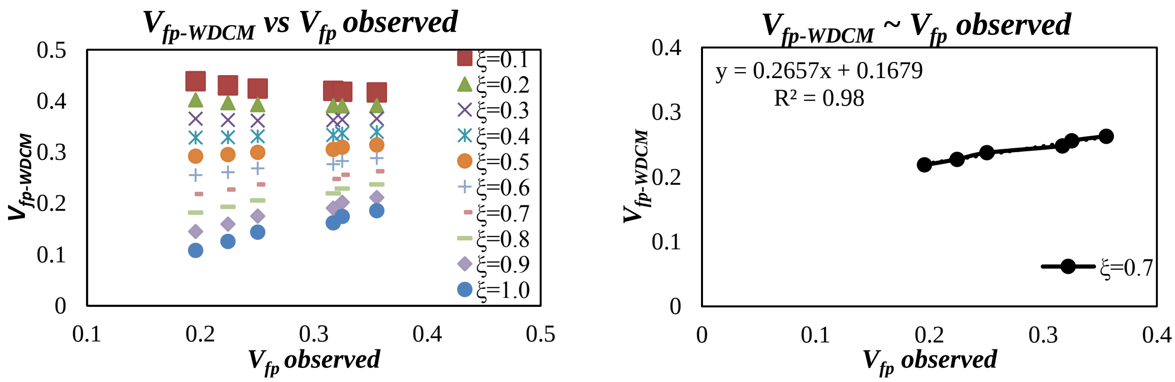


Fig 5.3(b) $V_{fp\text{-}WDCM}$ ~ V_{fp} ***observed*** **plot for ξ=0 to 1 and for ξ=0.7 with maximum R^2 for Roughness-1**

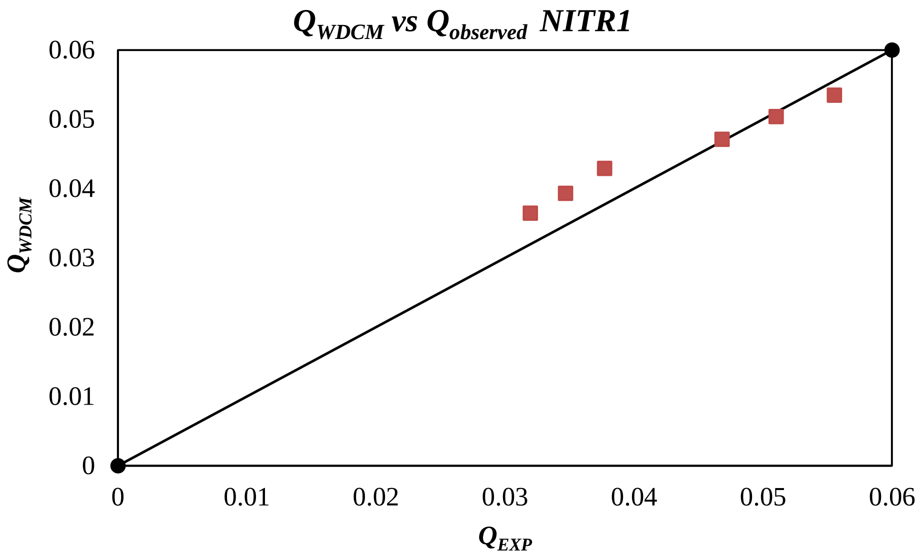


Fig 5.3(c) Q_{WDCM} ***vs*** Q_{EXP} **for Roughness-1**

Roughness-2

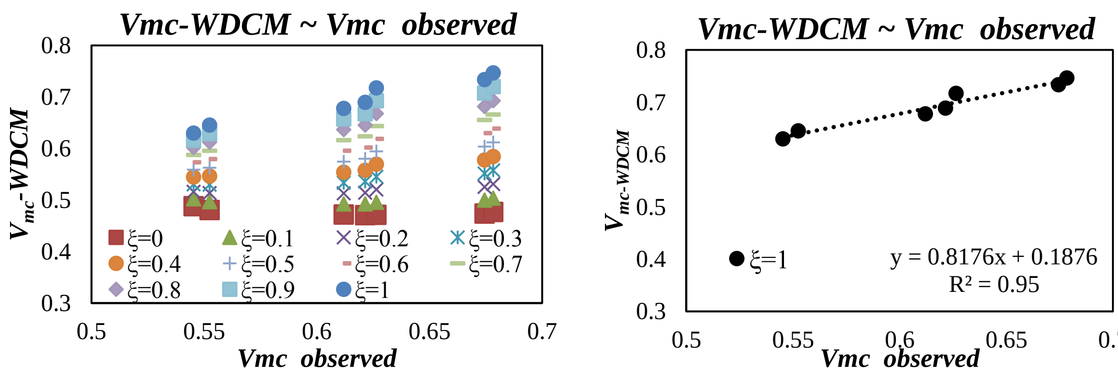


Fig 5.4(a) $V_{mc\text{-}WDCM}$ ~ V_{mc} ***observed*** **plot for ξ=0 to 1 and for ξ=1 with maximum R^2 for Roughness-2**

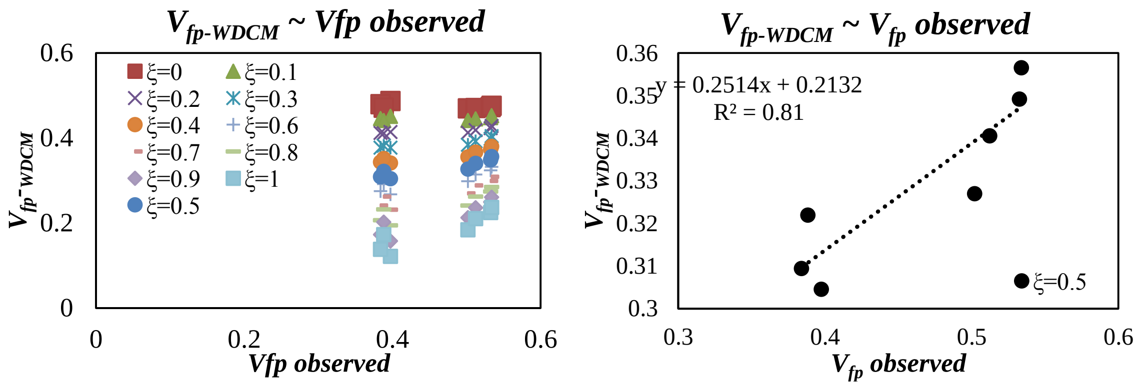


Fig 5.4(b) $V_{fp\text{-}WDCM}$ ~ V_{fp} *observed* plot for ξ=0 to 1 and for ξ=0.5 with maximum R^2 for Roughness-2

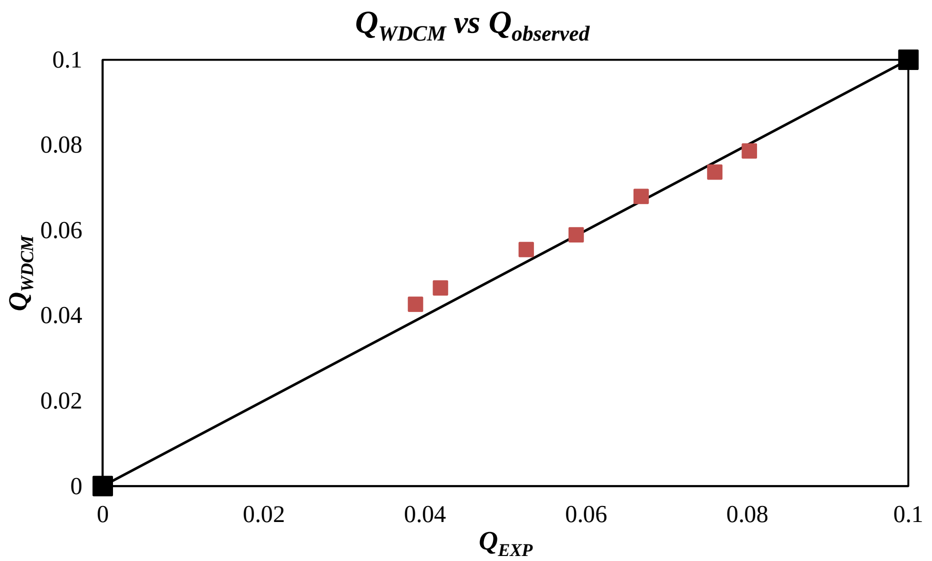


Fig 5.4(c) Q_{WDCM} *vs* Q_{EXP} for Roughness-2

5.2.1 Observations

The velocity in main channel and flood plain have been calculated through WDCM considering ξ=0.1, 0.2 to 1 for both type of experimentation. From figure 5.3 (a) and 5.3 (b), the results show that there is a maximum coefficient of regression observed for main channel velocity when the ξ=0.4 and 0.7 for flood plain. These results have been noticed for the first set of experiments having plastic mat on flood plain (Roughness-1). The maximum R^2 values are 0.96 and 0.98 for main channel and flood plain respectively. Then the discharges by this WDCM have been predicted for six over bank flow depths. The average error from this method is found 7.7% in terms of mean absolute percentage error (MAPE) for roughness-1. From figure 5.3 (c), it is found that WDCM predicts the flow rate more accurately for higher flow depth cases as compared to the lower flow depth cases.

By observing figure figure 5.4 (a) and 5.4 (b), it can be noted that for roughness-2, the maximum co-efficient of regression for main channel velocity is observed when ξ=1 and 0.5 for flood plain. The maximum R^2 values are 0.95 and 0.81 for main channel and flood plain respectively. From figure 5.4 (c), the same observation was found as for roughness-1 that the WDCM predicts the discharge more accurately for higher flow depth cases as compared to lower flow depth cases. For the second set of experiments that is flood plain having small gravel on its bed, the error found to be 4.78 % in terms of mean absolute percentage error (MAPE).

5.3 The Coherence Method

Ackers (1991) first proposed the Coherence Method. Coherence (COH) is defined as the ratio of the discharge calculated by single channel method with perimeter weighting of the friction factor to the summation of discharges of sub-areas calculated by vertical division method, and is given as

$$COH = \frac{\sum_{i=1}^{i=n} A_i \sqrt{\sum_{i=1}^{i=n} A_i / \sum_{i=1}^{i=n}(f_i P_i)}}{\sum_{i=1}^{i=n}\left[A_i \sqrt{A_i/(f_i P_i)}\right]} \qquad (5.07)$$

Where *i* defines each sub-area of *n* flow zones (for example *n=2* for the present channel using a vertical division), A_i area of each sub-area, P_i is the wetted perimeter of each sub-area and *f* is the Darcy-Weisbach friction factor. The coherence can also be expressed in terms of geometric ratios, which is given by the equation 5.08

$$COH = \frac{(1+A_*)X\sqrt{(1+A_*)/(1+P_* f_*)}}{1+A_*\sqrt{A_*/(P_* f_*)}}$$

(5.08)

Where $A_* = N_f A_{fp}/A_{mc}$;$P_* = N_f P_{fp}/P_{mc}$; $f_* = f_{fp}/f_{mc}$, N_f is the number of flood plain, A_{fp} and A_{mc} are the area of flood plain and main channel respectively, P_{fp} and P_{mc} are the wetted perimeter of flood plain and main channel. For the present experiment on the asymmetric compound channel the value of N_f is one as there is one flood plain.

As the *COH* value tends towards one, then the channel may be treated as a single channel that implies the interaction between various sub-areas may be considered negligible. But when the value of *COH* is significantly less than one, then it is required to estimate a new coefficient called discharge adjustment factor (*DISADF*), so that the discharge of each subsection can be corrected. Vertical division lines are generally used to separate a compound channel into sub-areas, which are not included in the calculation of wetted perimeter of each sub-area. Then using Manning's formula, discharge of each sub-area is calculated and added to obtain the 'basic' discharge (Q_{basic}). Then *DISADF* is calculated using equation 5.09, which is given below.

$$DISADF = \frac{Actual\ Discharge}{Basic\ Discharge} = \frac{Q_{actual}}{Q_{basic}} \tag{5.09}$$

Figure 5.9 shows a typical plot between relative depth and *DISADF*, where relative depth (D_r) is the ratio of flood plain flow depth and main channel flow depth ($D_r = (H-h)/H$). Ackers deduced four discrete behaviour for four distinct water level regions. To correct the DCM in each given region, Ackers developed four empirical equations using the FCF (Flood Channel Facility) data and data of other researchers.

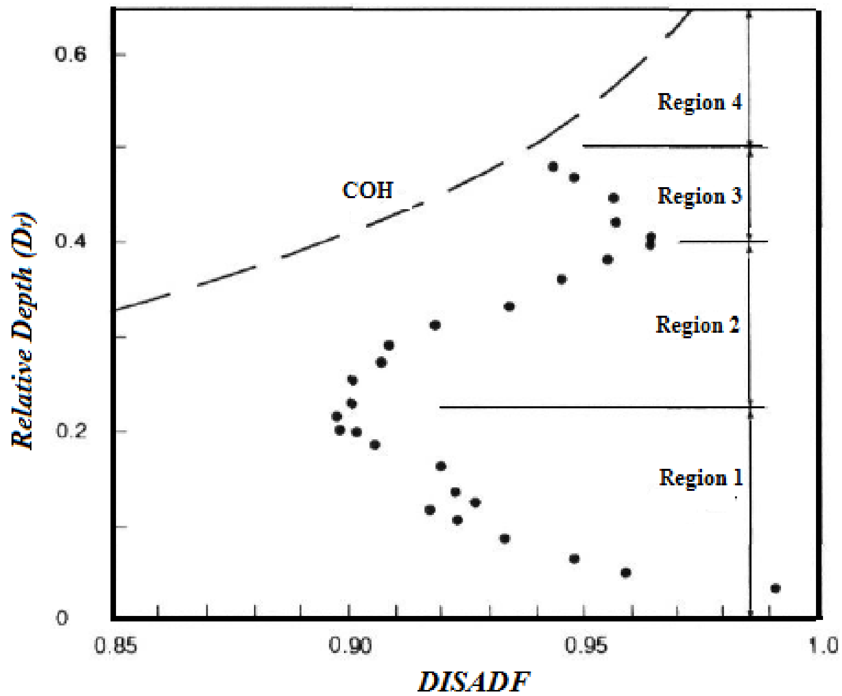


Fig 5.5: Relative Depth vs DISADF Plot

The different regions are

Region-1

This the region of relatively low flow depths where the momentum transfer increases with depth. A new factor introduced for this region called as discharge deficit (*DISDEF*). Where

$$DISDEF = \left(Q_{*2c} + N_f Q_{*2f}\right)\left(V_c - V_f\right) \times Hh \times ARF \tag{5.10}$$

$$Q_{*2c} = -1.240 + (0.395 \times B/w_c) + GH_* \tag{5.11}$$

$$Q_{*2f} = -1.0 H_* f_c/f_f \tag{5.12}$$

For $S_c \geq 1.0$: $G = 10.42 + 0.17\ f_f/f_c$ (5.13)

$S_c < 1.0$: $G = 10.42 + 0.12\ S_c f_f/f_c + 0.34(1 - S_c)$ (5.14)

Where V_c= calculated basic velocity in main channel

V_f= calculated basic velocity in flood plains

ARF= aspect ratio factor, typically $b/10h$

B = width of section including flood plain(s) at elevation of flood plain(s)

w_c = top width of main channel at elevation of flood plain(s)

H_* = relative depth

S_c = side slope of main channel

Then $Q_{R1} = Q_{basic} - DISDEF$ (5.15)

Where Q_{R1} is the required flow prediction for region-1

Region-2

This is the zone of higher flow depth where the interference effect decreases again. For this region, the coherence is calculated for a higher relative depth than the actual relative depth. Then this new coherence is used to adjust the basic discharge. To calculate the new coherence a modified flow depth *(H')* is used. Where

$$H' = Hh/(h - shift \times H) \quad (5.16)$$

Where for $S_c \geq 1.0$, $shift = 0.05 + 0.05N_f$ (5.17)

$S_c < 1.0$, $shift = -0.01 + 0.05N_f + 0.6S_c$ (5.18)

Then by using the shifted depth *H'* the *COH* is calculated as given in equation 5.08. After calculating the shifted *COH,* discharge prediction for region-2 is done using the equation 5.19.

$$Q_{R2} = Q_{basic} \times DISADF_2 \quad (5.19)$$

Where Q_{R2} is the corrected discharge for region-2 and $DISADF_2$ = shifted *COH.*

Region-3

Region-3 is a narrow region of flow, which occurs with further increase in floe depth, which cause an increase in interference again. The prediction of discharge for region-3 is done using equation 5.20.

$$Q_{R3} = Q_{basic} \times DISADF_3 \tag{5.20}$$

Where $DISADF_3 = 1.567 - 0.667\ COH$ (5.21)

In equation 5.21, the *COH* is calculated for the actual relative depth.

Region-4

In this region, the coherence of the section is such that the channel may be treated as a single section. However, it does not mean that the discharge calculated by DCM will provide correct results. However to calculate the discharge capacity for this region the following equations are used.

$$DISADF_4 = COH \tag{5.22}$$

$$Q_{R4} = Q_{basic} \times DISADF_4 \tag{5.23}$$

To predict the appropriate region of flow, the following equations are used.

If $Q_{R1} \geq Q_{R2}$ $then\ Q = Q_{R1}$ (5.24)

If $Q_{R1} < Q_{R2}$ and $Q_{R2} \leq Q_{R3}$ then $Q = Q_{R2}$ (5.25)

If $Q_{R1} < Q_{R2}$ and $Q_{R3} < Q_{R2}$ then $Q = Q_{R3}$

Unless $Q_{R4} > Q_{R3}$ when $Q = Q_{R4}$ (5.26)

The coherence method was applied to the present experimental channel for both roughness cases as well as other researcher's data, which includes both symmetrical and asymmetrical compound channels. The properties of the various channels, which were taken for this study given in table number 5.2 and 5.3.

Table 5.2: Resume of the Symmetrical compound channel data sets

Reference	*b(m)*	*B(m)*	*h(m)*	S_c	*H(m)*	S_0	n_{fp}	n_{mc}	$Q(m^3/s)$
FCF S01	1.5	10	0.15	1	0.1589-0.2501	0.001027	0.01	0.01	0.2082-1.0145
FCF S02	1.5	6.3	0.15	1	0.1565-0.2879	0.001027	0.01	0.01	0.2123-1.1142
FCF S03	1.5	3.3	0.15	1	0.1580-0.2992	0.001027	0.01	0.01	0.2251-0.8360
Mohanty (2013)	0.33	3.95	0.065	1	0.073-0.115	0.0011	0.01	0.01	0.0135-0.1062
Khatua (2007)	0.12	0.44	0.12	0	0.1364-0.2222	0.0019	0.011	0.011	0.0087-0.0391
Yang et al. (2007)	0.8	3	0.2	1.75	0.205-0.341	0.002	0.022	0.022	0.1607-0.4905
Rezaei S1 (2006)	0.398	0.598	0.05	0	0.0528-0.1077	0.002003	0.0088	0.0088	0.0120-0.0451

Rezaei S2 (2006)	0.398	0.798	0.05	0	0.0527-0.1045	0.002003	0.0088	0.0088	0.0120-0.0500
Rezaei S3 (2006)	0.398	0.998	0.05	0	0.0533-0.0974	0.002003	0.0088	0.0088	0.0120-0.0501
Rezaei S4 (2006)	0.398	1.198	0.05	0	0.0547-0.0940	0.002003	0.0088	0.0088	0.0121-0.0501
Atabay (2001)	0.398	1.2126	0.05	0	0.0596-0.0954	0.002024	0.0091	0.0091	0.0155-0.0553
Knight & Demetriu S1 (1983)	0.152	0.304	0.076	0	0.0852-0.1498	0.000966	0.01	0.01	0.0052-0.0171
Knight & Demetriu S2 (1983)	0.152	0.456	0.076	0	0.0875-0.1492	0.000966	0.01	0.01	0.0050-0.0234
Knight & Demetriu S3 (1983)	0.152	0.610	0.076	0	0.0850-0.1538	0.000966	0.01	0.01	0.0049-0.0294
Wormleaton et al.S1 (1982)	0.29	1.21	0.12	0	0.1351-0.1899	0.00043	0.011	0.01	0.0134-0.0435
Wormleaton et al.S2 (1982)	0.29	1.21	0.12	0	0.1351-0.1449	0.00094	0.011	0.01	0.0172-0.0292

Table 5.3: Resume of the Asymmetrical compound channel data sets

Reference	*b(m)*	*B(m)*	*h(m)*	S_c	*H(m)*	S_0	n_{fp}	n_{mc}	$Q(m^3/s)$
NIT R1	0.33	1.19	0.11	1	0.134-0.165	0.001	0.024	0.01	0.034-0.0596
NIT R2	0.33	1.19	0.11	1	0.14-0.181	0.001	0.02	0.01	0.0402-0.0820
FCF S06	1.5	4.05	0.15	1	0.15826-0.30185	0.001027	0.01	0.01	0.2235-0.9292
Khatib et al. (2013)	0.1	0.3	0.02	0	0.049-0.110	0.0025	0.015	0.015	0.0033-0.0144
Bousmar (2002)	0.4	0.8	0.05	0	0.0543-0.0912	0.00099	0.0107	0.0107	0.00782-0.02204
Atabay (2001)	0.398	0.8053	0.05	0	0.0593-0.1095	0.002024	0.0091	0.0091	0.015-0.0554
Myers (1978)	0.254	0.61	0.102	0	0.1116-0.1684	0.0002646	0.01	0.01	0.0063-0.0182
James & Brown T5 (1977)	0.1778	0.4696	0.0508	1	0.05578-0.08016	0.001-0.003	0.012	0.011	0.00708-0.01467
James & Brown T7 (1977)	0.1778	0.8509	0.0508	1	0.05456-0.08168	0.001-0.003	0.011	0.01	0.00558-0.01433

For all the channels given in table 5.2 and 5.3, coherence method was applied by using equations from 5.08 to 5.23. To select the appropriate region of flow, equation 5.24, 5.25 and 5.26 were used.

5.4 Model Development

5.4.1 Multiple regression analysis

In statistics, regression analysis is done to evaluate necessary relation between variables, which includes various techniques for modelling and analysing several variables. Regression analysis helps us to estimate a proper correlation between a response (criterion) variable and one or more regressor variables (or predictors). More precisely, it enables us to perceive the effect of one varying independent parameter on the dependent parameter while the other independent variables are kept constant. Regression analysis is widely used for predicting and forecasting.

Multiple regression analysis is a capable strategy used to anticipate the obscure estimation of a variable from two or more known variables. More specifically, multiple regression analysis helps us to anticipate the estimation of "y" for given estimation of x_1, $x_2 \ldots x_n$. We can likewise concentrate the individual impact of the known factors on the obscure parameter. The standard basis of multiple regression is to know more about the association between a few autonomous or predictor factors and a dependent or paradigm variable. Multiple regression analysis is used to predict dependent variables from a number of independent variables.

In this present study, for implementing multiple regression analysis discharge adjustment factor (DISADF) was taken as dependent variable and width ratio ($\alpha = B/b$), aspect ratio ($\delta = b/h$), relative depth ($D_r = (H - h)/H$), friction factor ratio ($f_r = f_{fp}/f_{mc}$), and bed slope (S_0) were taken as independent variable. A number of single regression models were developed as one to one relationship between the dependent variable (*DISADF*) and the independent variables (width ratio, aspect ratio, relative depth, friction factor ratio and bed slope). Based on the highest coefficient of regression (R^2) values, best single regression models were selected. The total regression analysis procedure for the present study divided into two parts, one for symmetrical compound channel sections and other part for asymmetrical channel section.

5.4.1.1 Regression Models for Symmetrical Compound Channels

All the channels, which were taken for coherence method study also taken for present modelling. All the geometric and roughness parameters of the channels are given in table 5.2. The single regression plots between the dependent parameter (*DISADF*) and independent parameters (relative depth, width ratio, friction factor ratio, aspect ratio and bed slope) are given in figure 5.6.

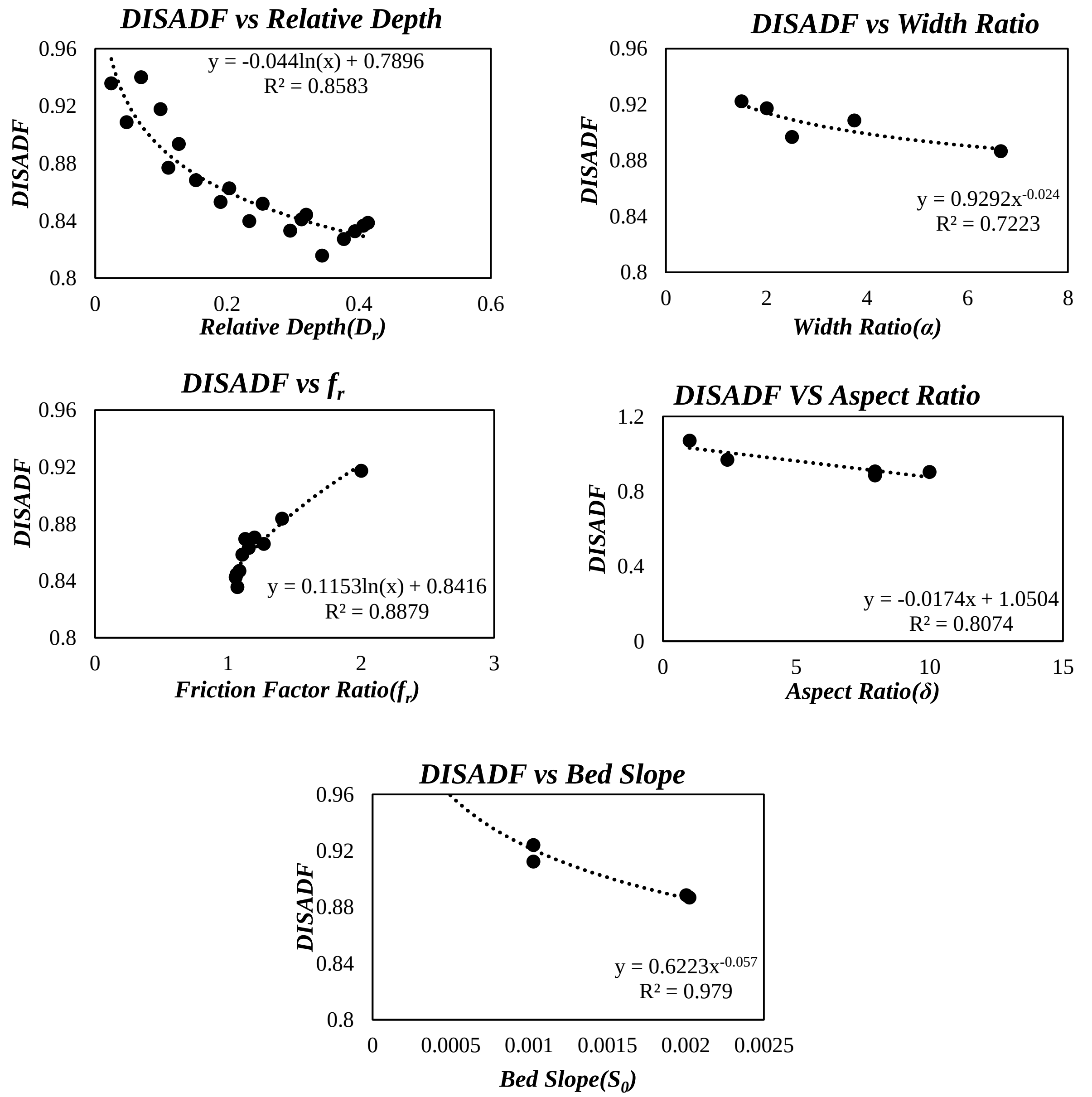


Fig 5.6: DISADF vs Relative Depth, Width Ratio, Friction Factor Ratio, Aspect Ratio and Bed slope plots with highest R^2 value for symmetrical channels

The relationships between *DISADF* and relative depth, width ratio, friction factor ratio, aspect ratio and bed slope are given in table 5.4.

Table 5.4: Relationships between dependent and independent parameters for symmetrical channels

Parameter	Relation	Function	R^2
Relative Depth (D_r)	DISADF = -0.044ln(D_r) + 0.7896	Logarithmic	0.8583
Width Ratio (α)	DISADF = 0.9292(α) $^{-0.024}$	Power	0.7223
Friction Factor Ratio (f_r)	DISADF = 0.1153ln(f_r) + 0.8416	Logarithmic	0.8879
Aspect Ratio (δ)	DISADF = -0.0174(δ)+ 1.0504	Linear	0.8074
Bed Slope (S_0)	DISADF = 0.6223(S_0)$^{-0.057}$	Power	0.9790

Then multiple regression analysis was applied using single regression relationships between the dependent variable DISADF and all the five independent variables relative depth, width ratio, friction factor ratio, aspect ratio and bed slope. The final equation for DISADF for symmetrical channles found to be

$$DISADF = (-0.048\ln(D_r)) + (1.18\alpha^{-0.024}) - (0.203\ln(f_r)) - (0.003\delta) + (0.421S_0^{0.057}) - 0.81 \tag{5.27}$$

By using the above equation, DISADFs for all the symmetrical channels which were taken for this study were recalculated. After getting the DISADFs for all the channels, discharges can be predicted using the formula $Q_{pre} = Q_{VDM} \times DISADF$, where Q_{pre} is the predicted discharge using the new model and Q_{VDM} is the discharge calculated by vertical division method.

5.4.1.2 Regression Models for Asymmetrical Compound Channels

All the asymmetric compound channels, which were taken for coherence method study also taken for present modelling. All the geometric and roughness properties of the channels are given in table 5.3.

The single regression plots between the dependent parameter (*DISADF*) and independent parameters (relative depth, width ratio, friction factor ratio, aspect ratio and bed slope) are given in figure 5.7.

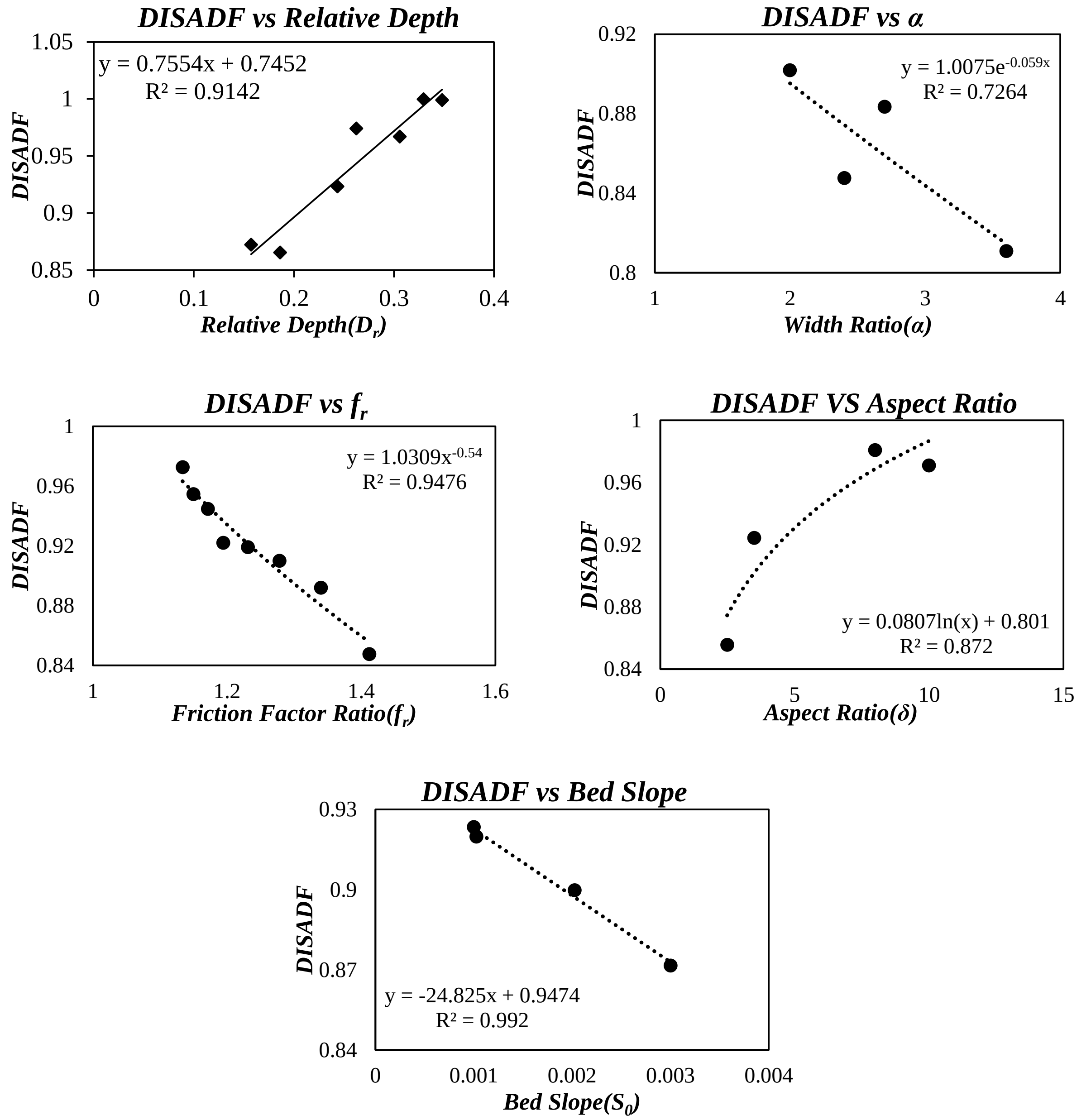


Fig 5.7: DISADF vs Relative Depth, Width Ratio, Friction Factor Ratio, Aspect Ratio and Bed slope plots with highest R^2 value for asymmetrical channels

The relationships between *DISADF* and relative depth, width ratio, friction factor ratio, aspect ratio and bed slope are given in table 5.5.

Table 5.5: Relationships between dependent and independent parameters for asymmetrical channels

Parameter	Relation	Function	R^2
Relative Depth (D_r)	DISADF = 0.7554(D_r) + 0.7452	Linear	0.9142
Width Ratio (α)	DISADF = $1.0075e^{-0.059(\alpha)}$	Exponential	0.7264
Friction Factor Ratio (f_r)	DISADF = $1.0309(f_r)^{-0.54}$	Power	0.9476

Aspect Ratio (δ)	DISADF = 0.0807ln(δ)+ 0.801	Logarithmic	0.8720
Bed Slope (S_0)	DISADF = -24.825(S_0) + 0.9474	Linear	0.9920

To get the final equation of *DISADF* for asymmetrical compound channels, the same procedure was followed as in case of symmetrical compound channels. The equation is given in equation 5.28.

$$DISADF = (0.03D_r) - (0.184e^{-0.059\alpha}) + (0.049f_r^{-0.54}) + \left(0.02\ln(\delta)\right) - (9.641S_0) + 1.013 \tag{5.28}$$

Then the new DISADFs for all the asymmetric compound channels used in the present work were calculated using equation 5.28. After getting the DISADFs for all the channels, discharges can be predicted using the formula $Q_{pre} = Q_{VDM} \times DISADF$, where Q_{pre} is the predicted discharge using the new model and Q_{VDM} is the discharge calculated by vertical division method which is also called as bsaic discharge or conveyance.

5.5 Error Analysis

Error analysis is the study of quantification of error, or uncertainty that may be present in a model. Generally, error analysis is done to determine the strength or accuracy of a model. The different types of errors used to determine the accuracy of a model are Mean Percentage Errors (*MPE*), Mean Absolute Percentage Errors (*MAPE*) and Root Mean Square Errors (*RMSE*). For determining the strength of the model presented in this study, MAPE was used. The errors for various channels taken for this model were calculated using the formula

$$MAPE(\%) = \left|\frac{Q_{obs}-Q_{pre}}{Q_{obs}}\right| \times 100 \tag{5.29}$$

Errors resulted from discharge prediction by Coherence Method and the new model developed for both symmetrical and asymmetrical compound channels are presented in table 5.6 and 5.7 respectively, which is given below.

Table 5.6: Percentage errors for Symmetrical compound channel data sets

Series	**Errors (*MAPE*) (%)**	
	Coherence Method	**New Model**
Mohanty (2013)	14.9727	5.9373
Khatua (2007)	7.8049	4.5958
Yang et al. (2007)	2.8161	4.9126

Rezaei S1 (2006)	6.9885	1.9396
Rezaei S2 (2006)	7.4683	10.051
Rezaei S3 (2006)	2.4999	1.6088
Rezaei S4 (2006)	3.1772	2.7882
Atabay (2001)	4.2926	4.4030
Natural River (Ackers, 1991)	2.5305	5.3065
FCF S01	2.1531	2.2679
FCF S02	1.1773	2.4083
FCF S03	0.5503	2.2999
Knight & Demetriu S1 (1983)	8.1733	4.4284
Knight & Demetriu S2 (1983)	7.7619	6.0558
Knight & Demetriu S3 (1983)	4.4324	2.5261
Wormleaton et al. S1 (1982)	10.9798	3.8376
Wormleaton et al. S2 (1982)	14.0831	13.2551

Table 5.7: Percentage errors for Asymmetrical compound channel data sets

Series	Errors (%)	
	Coherence Method	New Model
FCF S06	13.0324	3.4229
NIT R1	7.1323	6.3211
NIT R2	8.6501	5.9149
Bousmar (2002)	1.5042	2.2679
Atabay (2001)	2.0107	2.2895
Myers (1978)	5.6172	3.7084
James & Brown T5 (1977)	8.2359	4.8089
James & Brown T7(1977)	8.1882	2.9464
River Trent	3.2671	5.1548

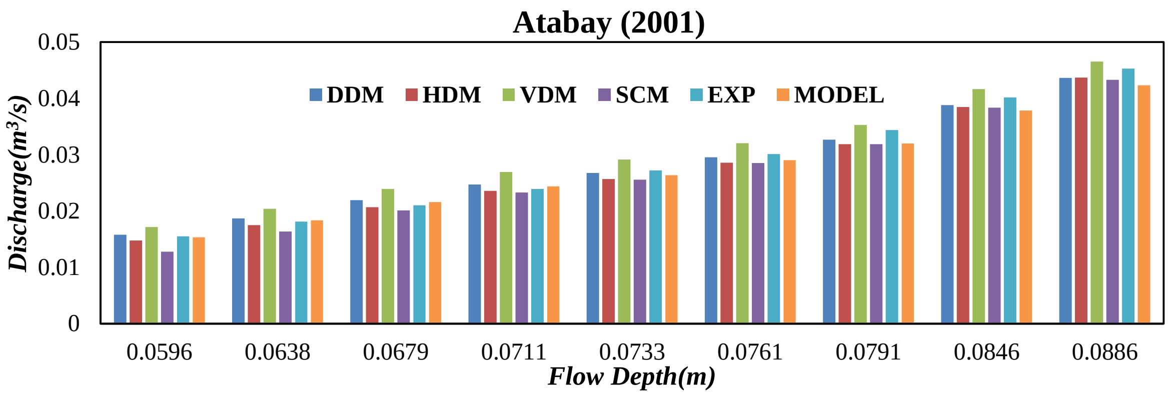
5.5.1 Discussions

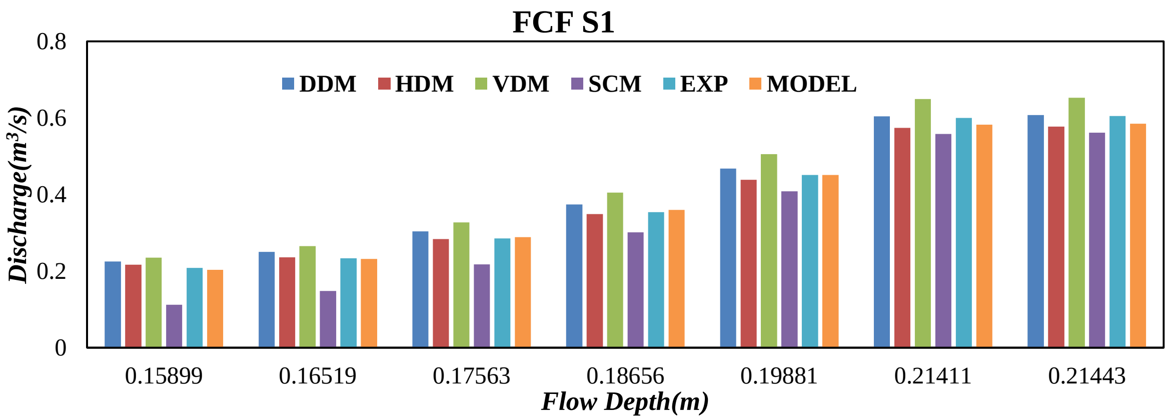
From table 5.4, it is observed that in some cases the error resulted from the new model is less than the error resulted from coherence method and in some cases the error from new model is more than coherence method. For all the channels, the errors are below 10% except Rezaei S2 (2006) and Wormleaton et al. S2 (1982). For the natural river data set (Ackers 1991), the new model is giving good results with 5.31% error. The average error for all the symmetrical compound channels given in table 5.4 is found to be 4.6248%.

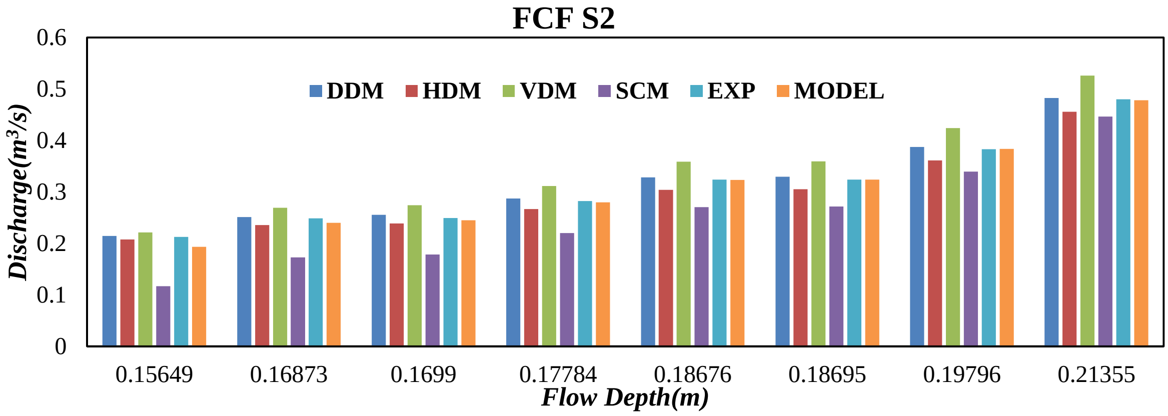
From table 5.5, it is found that the new model is predicting good discharge results with less than 5% error for all the asymmetrical compound channels except NITR1 and NITR2. For the natural river i.e. the river Trent, the error is found to be 5.1548%. The average error for all the asymmetrical compound channels given in table 5.5 is found to be 4.0927%.

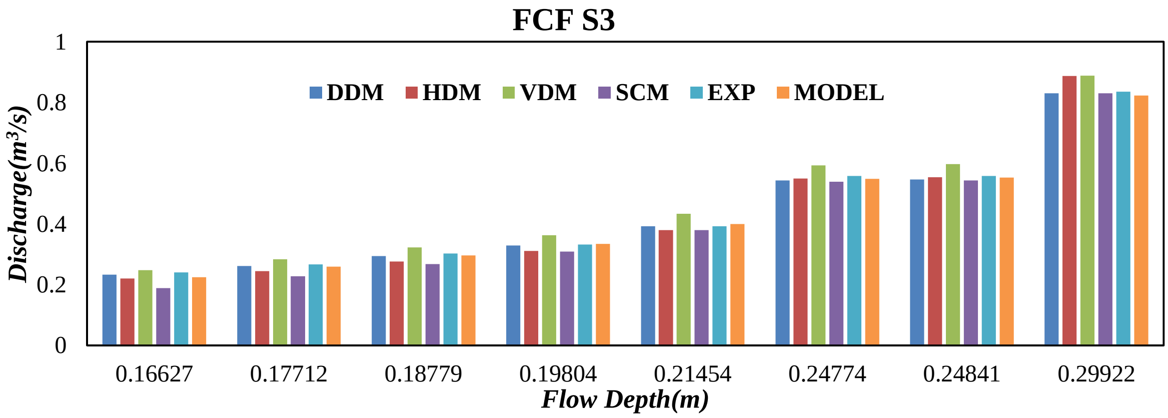
5.5.2 Error Analysis plots

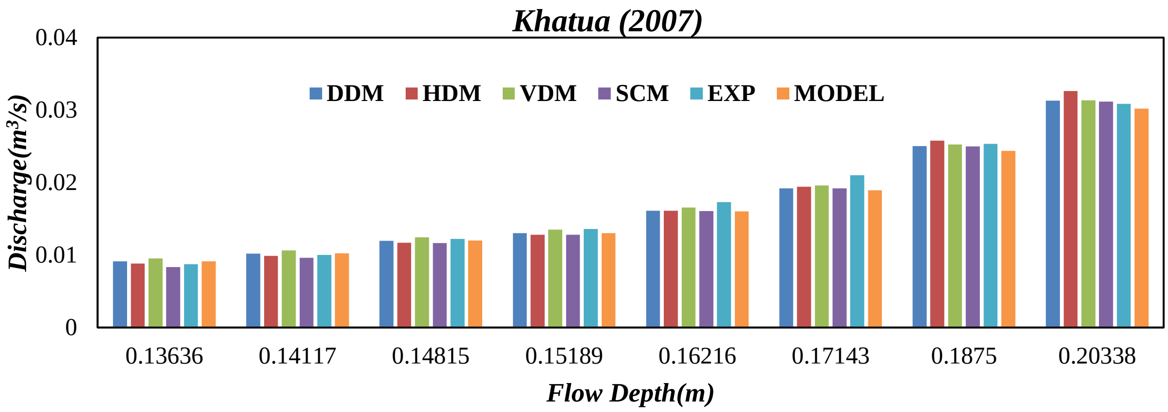
5.5.2.1 Symmetrical Compound Channels

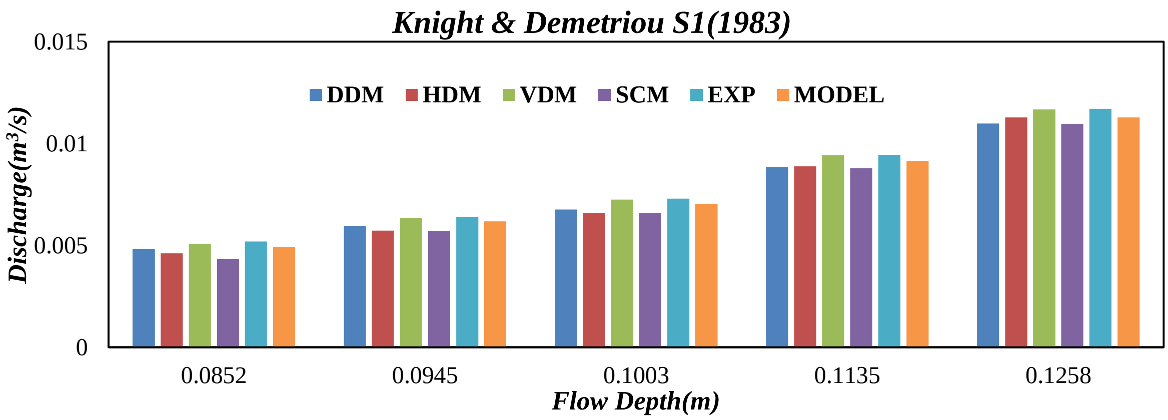


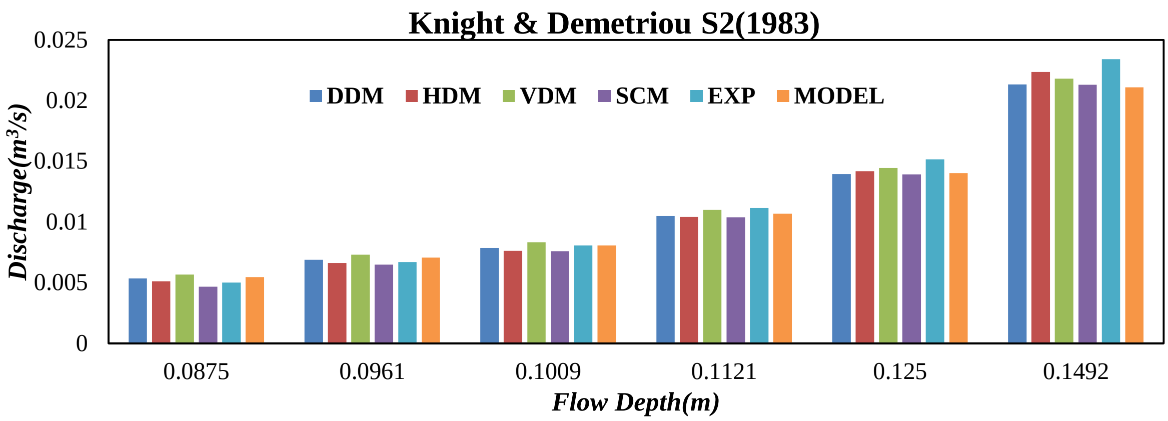


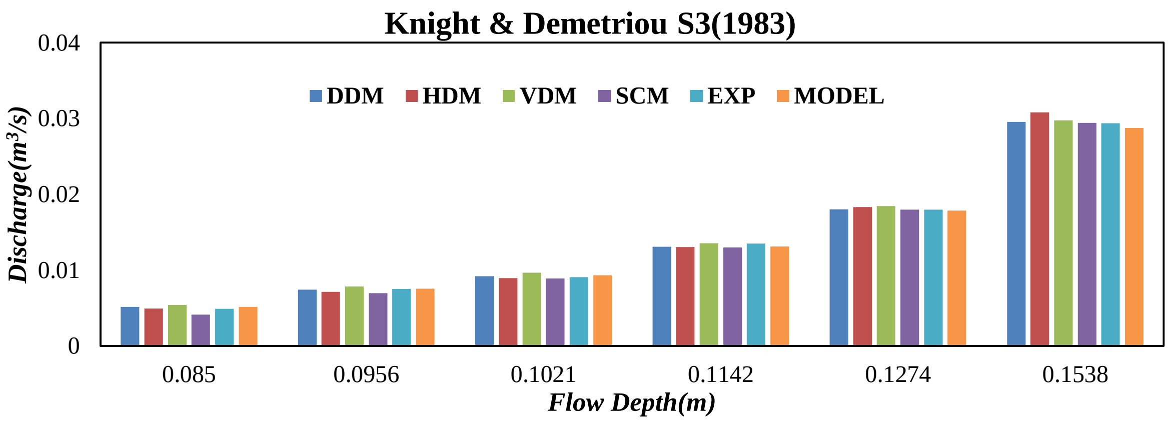

FCF S2
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0 0.1 0.2 0.3 0.4 0.5 0.6
0.15649 0.16873 0.1699 0.17784 0.18676 0.18695 0.19796 0.21355
Flow Depth(m)

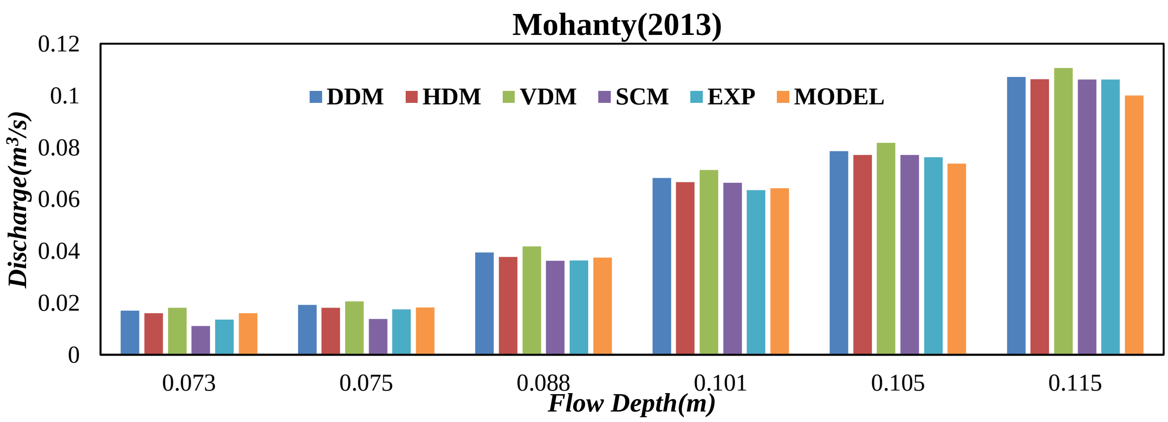

FCF S3
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0 0.2 0.4 0.6 0.8 1
0.16627 0.17712 0.18779 0.19804 0.21454 0.24774 0.24841 0.29922
Flow Depth(m)

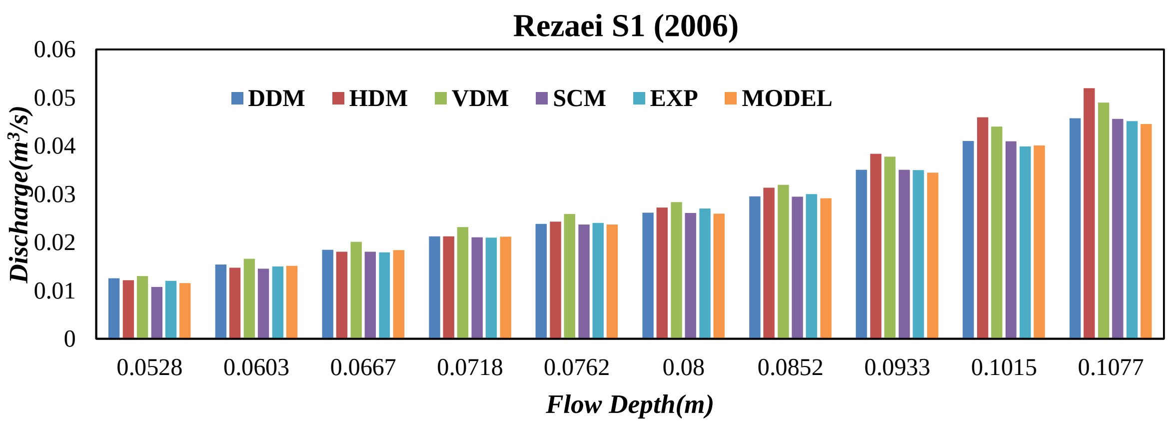

Khatua (2007)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0 0.01 0.02 0.03 0.04
0.13636 0.14117 0.14815 0.15189 0.16216 0.17143 0.1875 0.20338
Flow Depth(m)

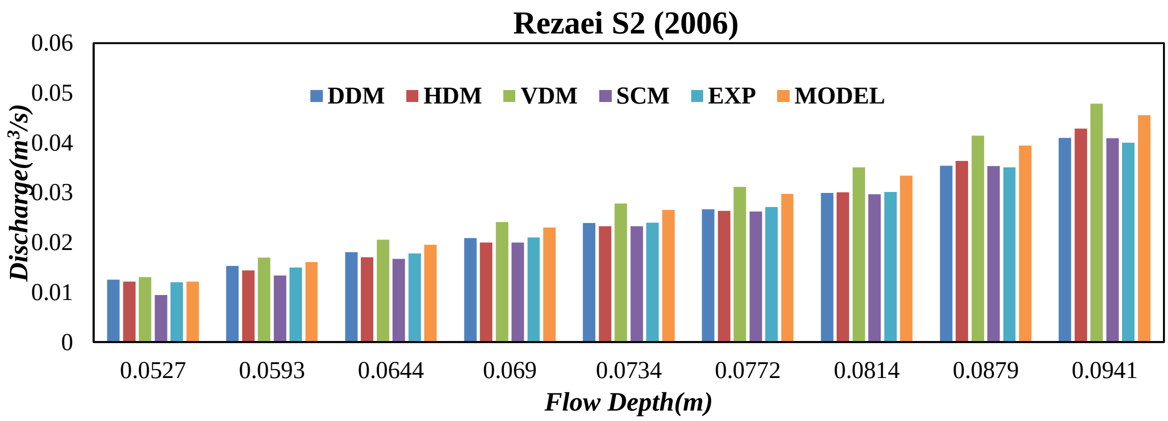

Knight & Demetriou S1(1983)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0 0.005 0.01 0.015
0.0852 0.0945 0.1003 0.1135 0.1258
Flow Depth(m)

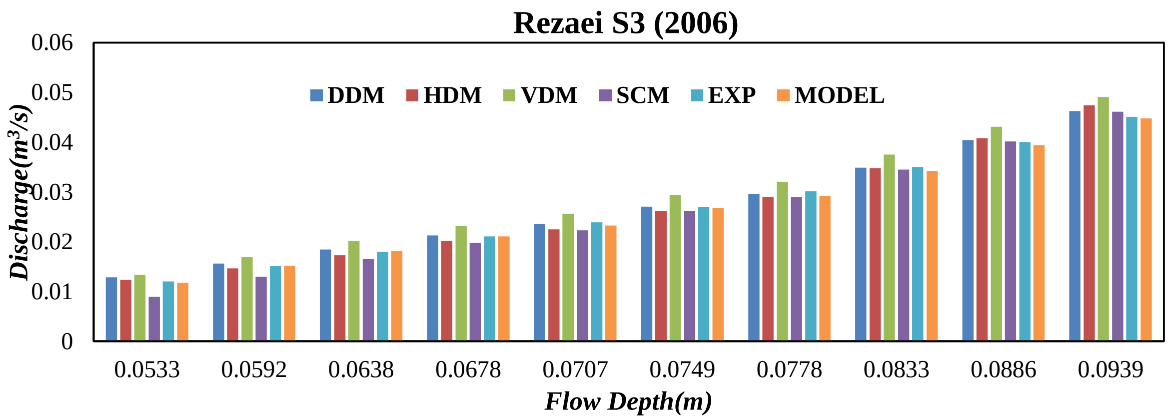

Knight & Demetriou S2(1983)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0.025
0.02
0.015
0.01
0.005
0
0.0875
0.0961
0.1009
0.1121
0.125
0.1492
Flow Depth(m)

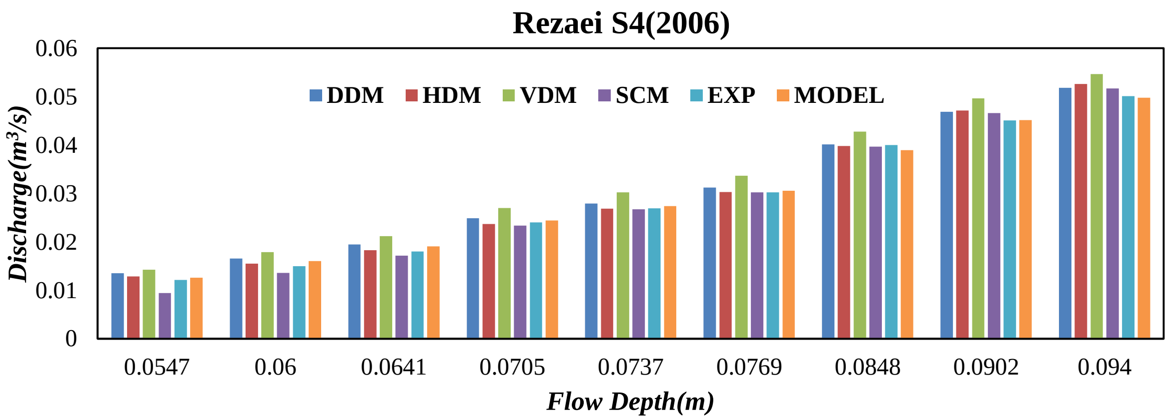

Knight & Demetriou S3(1983)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0.04
0.03
0.02
0.01
0
0.085
0.0956
0.1021
0.1142
0.1274
0.1538
Flow Depth(m)

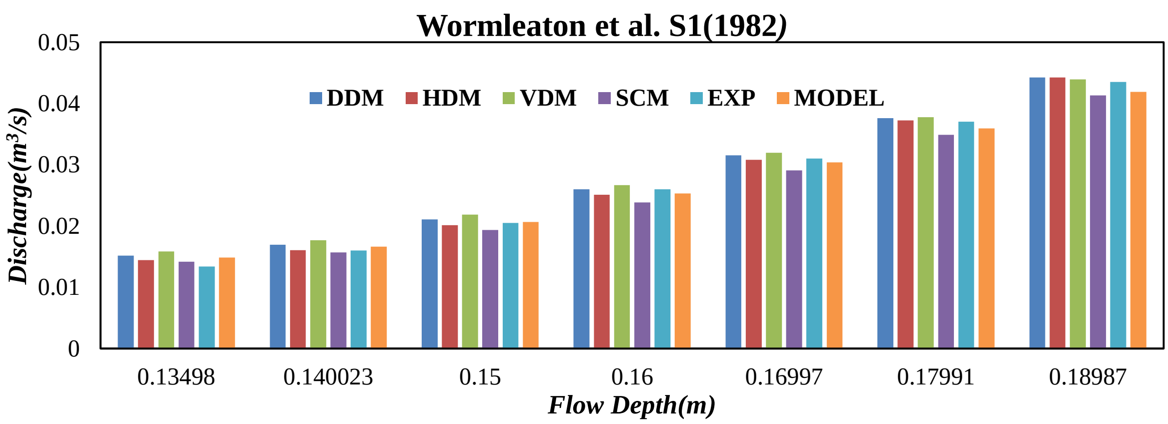

Mohanty(2013)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0.12
0.1
0.08
0.06
0.04
0.02
0
0.073
0.075
0.088
0.101
0.105
0.115
Flow Depth(m)


Rezaei S1 (2006)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0.06
0.05
0.04
0.03
0.02
0.01
0
0.0528
0.0603
0.0667
0.0718
0.0762
0.08
0.0852
0.0933
0.1015
0.1077
Flow Depth(m)


Rezaei S2 (2006)
DDM HDM VDM SCM EXP MODEL
Discharge(m^3/s)
0.06
0.05
0.04
0.03
0.02
0.01
0
0.0527 0.0593 0.0644 0.069 0.0734 0.0772 0.0814 0.0879 0.0941
Flow Depth(m)


Rezaei S3 (2006)
DDM HDM VDM SCM EXP MODEL
Discharge(m^3/s)
0.06
0.05
0.04
0.03
0.02
0.01
0
0.0533 0.0592 0.0638 0.0678 0.0707 0.0749 0.0778 0.0833 0.0886 0.0939
Flow Depth(m)


Rezaei S4(2006)
DDM HDM VDM SCM EXP MODEL
Discharge(m^3/s)
0.06
0.05
0.04
0.03
0.02
0.01
0
0.0547 0.06 0.0641 0.0705 0.0737 0.0769 0.0848 0.0902 0.094
Flow Depth(m)


Wormleaton et al. S1(1982)
DDM HDM VDM SCM EXP MODEL
Discharge(m^3/s)
0.05
0.04
0.03
0.02
0.01
0
0.13498 0.140023 0.15 0.16 0.16997 0.17991 0.18987
Flow Depth(m)

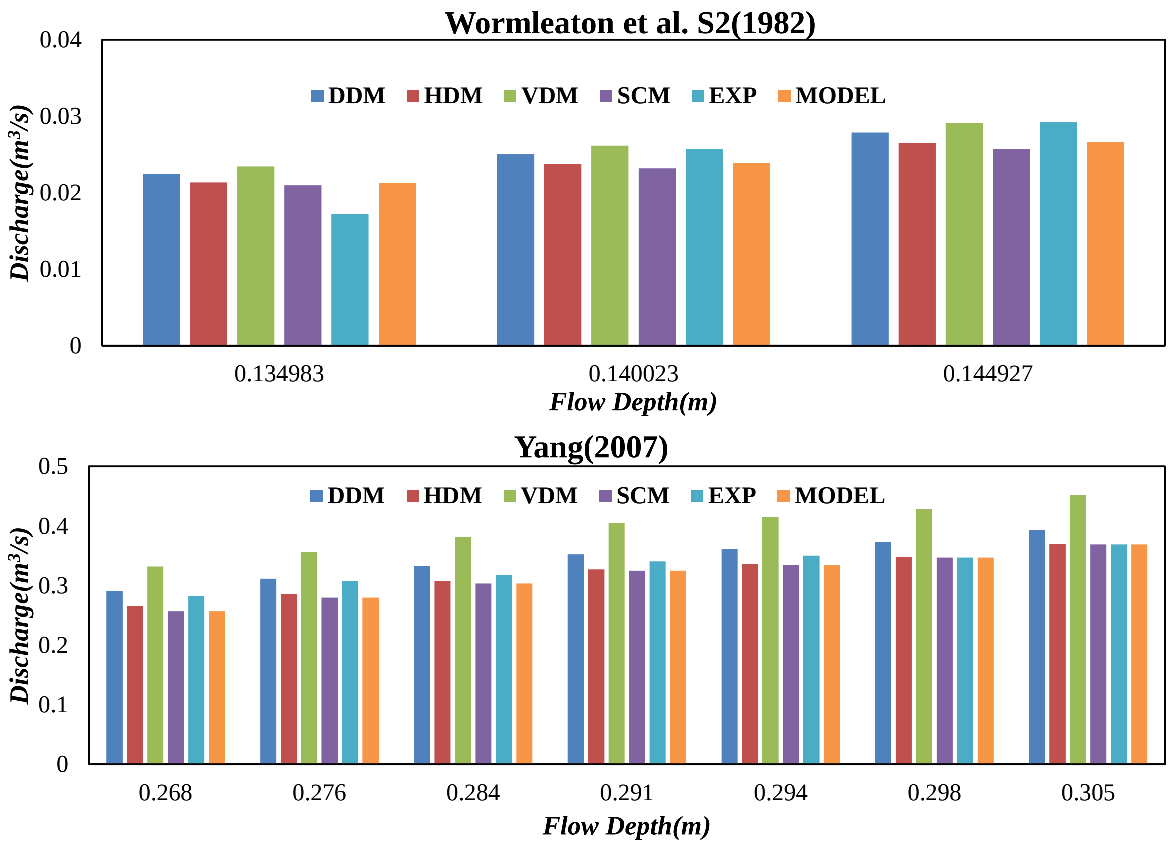
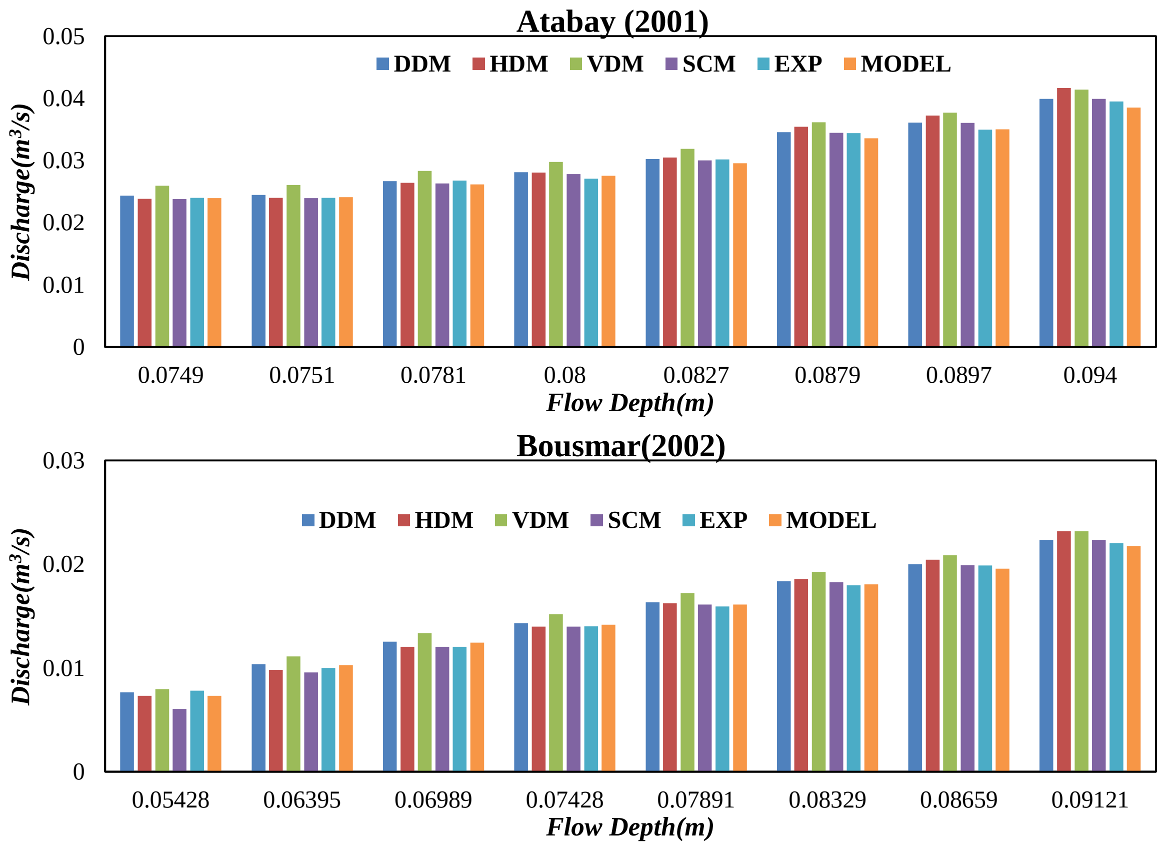
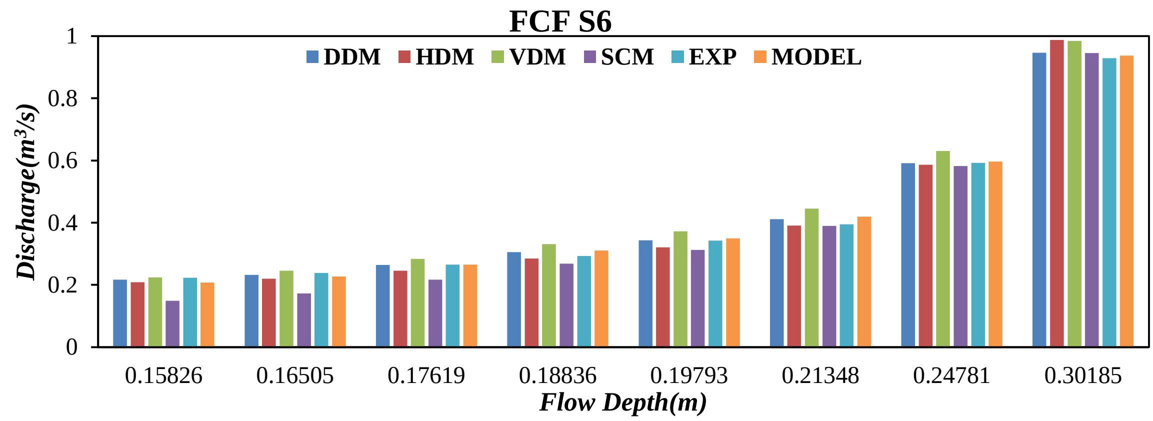
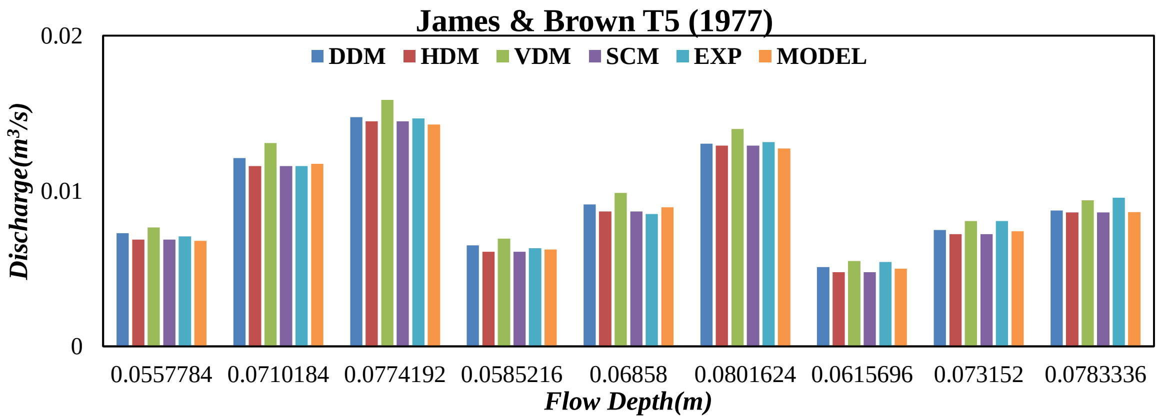


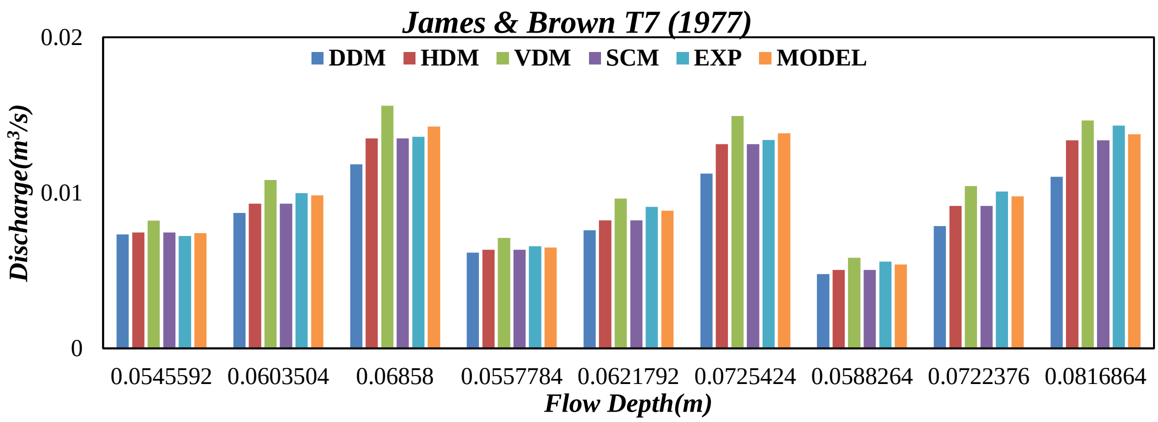
Fig 5.8 Resulted error from different approaches for symmetrical compound channels

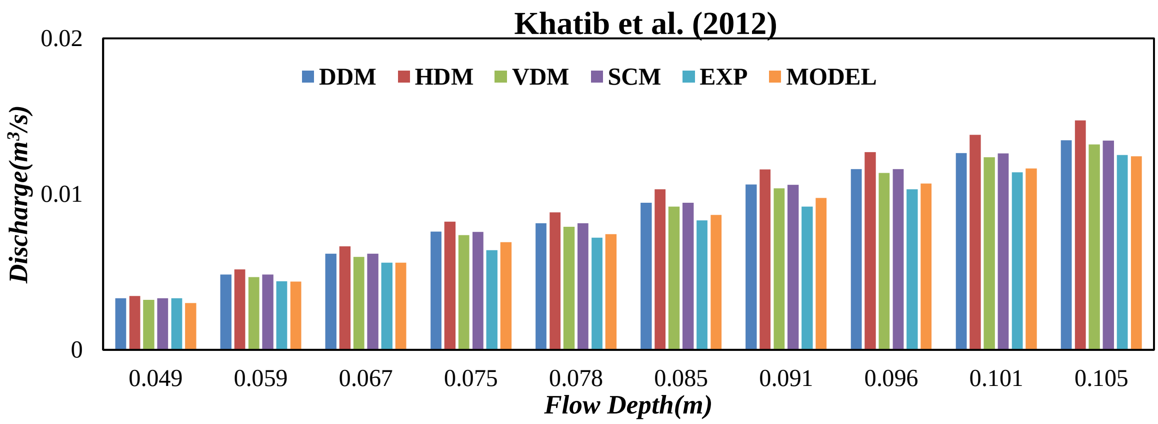
5.5.2.2 Asymmetrical Compound Channels




FCF S6
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
1
0.8
0.6
0.4
0.2
0
0.15826 0.16505 0.17619 0.18836 0.19793 0.21348 0.24781 0.30185
Flow Depth(m)


James & Brown T5 (1977)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0.02
0.01
0
0.0557784 0.0710184 0.0774192 0.0585216 0.06858 0.0801624 0.0615696 0.073152 0.0783336
Flow Depth(m)


James & Brown T7 (1977)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0.02
0.01
0
0.0545592 0.0603504 0.06858 0.0557784 0.0621792 0.0725424 0.0588264 0.0722376 0.0816864
Flow Depth(m)


Khatib et al. (2012)
DDM HDM VDM SCM EXP MODEL
Discharge(m³/s)
0.02
0.01
0
0.049 0.059 0.067 0.075 0.078 0.085 0.091 0.096 0.101 0.105
Flow Depth(m)

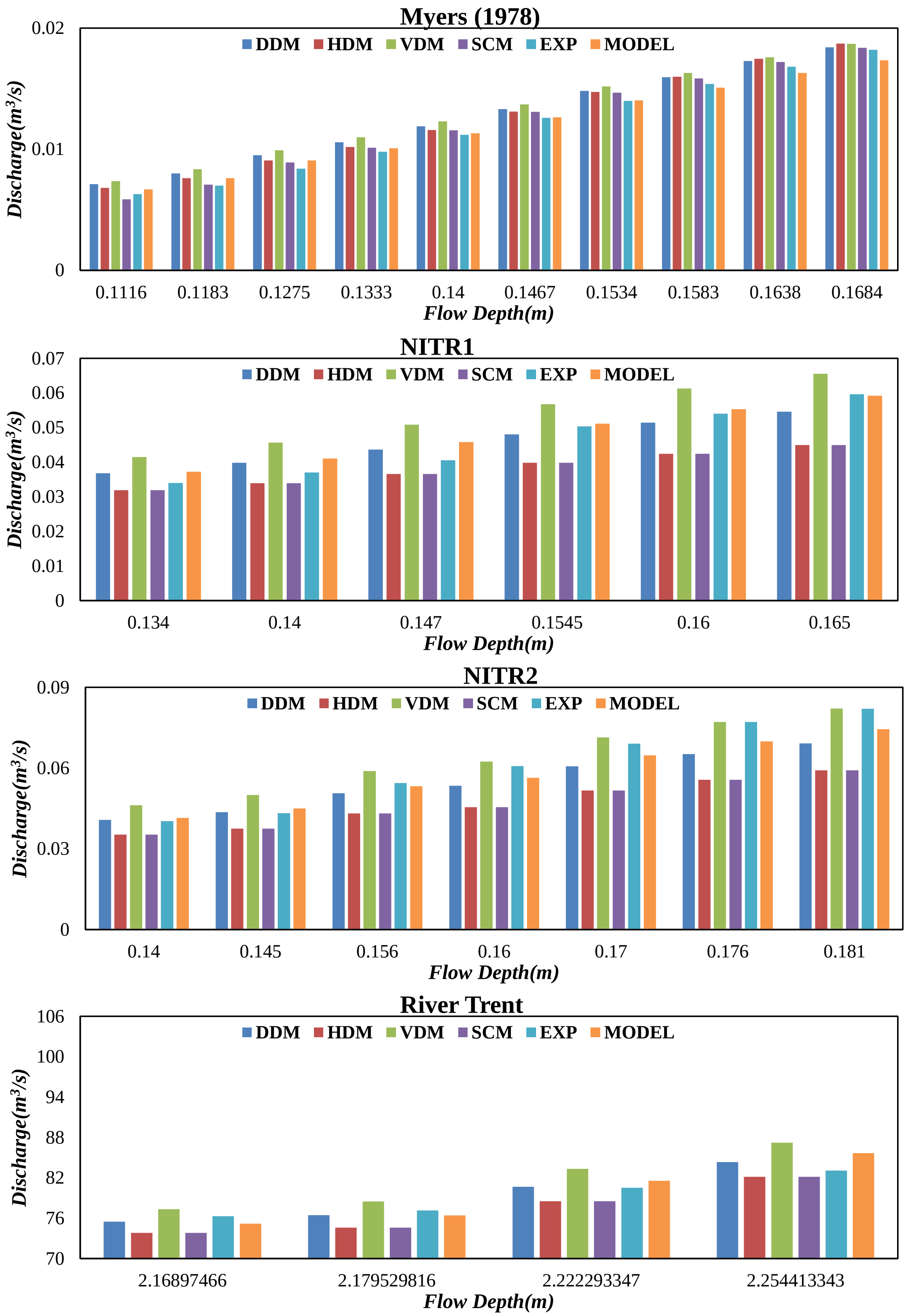


Fig 5.9 Resulted error from different approaches for asymmetrical compound channels

5.5.3 Discussions

Standard discharge prediction methods like single channel method (*SCM*) and divided channel method (*DCM*) have been used to predict the discharge and then these results were compared with the results of present model. All the results were compared and plotted. Figure 5.8 represents all the symmetrical compound channels taken and figure 5.9 represents all the asymmetrical compound channels taken in to account for the present study. The divided channel method includes diagonal division method (*DDM*), horizontal division method (*HDM*) and vertical division method (*VDM*). In all cases, VDM is over predicting the discharge. Among the three division methods, the DDM gives better prediction of discharge. It is also observed that in maximum cases SCM is under predicting the discharge. From fig, 5.8 and 5.9 it is seen that the HDM is not following any trend i.e. in some cases it is under predicting and in some cases it is over predicting. The present model is found to provide better results for low flow depth cases but for higher flow depth cases, it is giving an error of 5% to 6%.

Chapter-6

Conclusions and Scope of Future Work

6.1 Conclusions

Experiments have been conducted for the asymmetrical compound channel to analyze the effect of differential roughness on flow characteristics like depth-averaged velocity, boundary shear stress, stage-discharge relationships, energy and momentum correction factors etc. of an asymmetrical compound channel. Reviewing all the aspects of the present work, the following conclusions can be made.

1. The overall discharge is found to be increasing by increase in flow depth for all types of rough compound channels studied.
2. It is found that the depth averaged velocity increase as flow depth increases and for shallow depth cases, the fluctuation of depth averaged velocity at the interface of main channel and flood plain is more and become uniform for higher depths.
3. A comparison of same relative depth cases is also made for depth-averaged velocity plots of both the roughness conditions i.e. roughness-1 and roughness-2. From the comparison plots, it is found that the depth-averaged in roughness-1 condition is less than the velocity for roughness-2 condition. As the Manning's *n* of the flood plain material in roughness-1 is more than the roughness-2, the depth-averaged velocity is coming to be less for roughness-1 than roughness-2.
4. It has been observed that the boundary shear stress increases with increase in flow depth. The fluctuation of boundary shear stress is more in case of roughness-1 whereas the fluctuation is less for roughness-2 at the junction of variable and constant flow domain of the main channel. For higher differential roughness compound channel flow, the boundary shear stress in flood plain is less as compared to the lower differential roughness. For main channel no significant changes are seen as the main channel the roughness is same for both cases. When depth increases, the difference between the boundary shear stress of main channel and flood plain decreases and the gap is more in higher roughness case as compared to lower roughness cases.

5. For the experimental asymmetric compound channel, kinetic energy correction factors or simply energy correction factors and momentum correction factors have been calculated for each flow depth of both roughness-1 and roughnes-2. The values of energy correction factor and momentum correction factor are found to be in a range of 1.235 to 1.108 and 1.080 to 1.028 respectively for roughness-1. For roughness-2, energy and momentum correction factors are in a range of 1.189 to 1.057 and 1.066 to 1.002 respectively. It is also observed that these values decrease with increase in flow depth. As flow depth increases, the momentum transfer between fast moving main channel flow and slow moving flood plain decreases and the hydraulic properties of main channel and flood plain will be nearly same. Therefore, the correction factor values will tend towards one.
6. The weighted divide channel method (*WDCM*) is applied to the experimental compound channel for both roughness cases to find the values of weighting factor for main channel and flood plain flow. For roughness-1, the value of weighting factor (ξ) for main channel and flood plain is found to be 0.4 and 0.7 respectively. For roughness-2, the value of weighting factor (ξ) for main channel and flood plain is found to be 1 and 0.5 respectively. Using these weighting factors, improved mean velocity for main channel and flood plain is calculated and then discharge for the compound channel is predicted. It is observed that WDCM predicts the flow rate more accurately for higher flow depth cases as compared to the lower flow depth cases. The average error from this method is found 7.7% in terms of mean absolute percentage error (*MAPE*) for roughness-1. For the second set of experiments that is flood plain having small gravel on its bed, the error found to be 4.78 % in terms of mean absolute percentage error (*MAPE*).
7. Coherence method (Ackers, 1991) is used to predict the discharge of the experimental and other researchers' data, which includes both symmetrical and asymmetrical compound channels with smooth and differential channels. A factor called discharge adjustment factor (*DISADF*), which is the ratio of observed discharge and discharge predicted by vertical division method, is modelled. The average error for all the symmetrical compound channels included in this present study is found to be 4.6248% and for asymmetrical channels, it is predicting the discharge with an average error of 4.0927%. For the natural river data set (Ackers 1991), which is a symmetrical section, the

new model is giving good results with 5.31% error and for an asymmetrical river data set like river Trent, the error is found to be 5.1548%.

8. Standard discharge prediction methods like single channel method (*SCM*) and divided channel method (*DCM*) have been used to predict the discharge and then these results were compared with the results of present model. In all cases, VDM is over predicting the discharge. Among the three division methods, the DDM gives better prediction of discharge. It is also observed that in maximum cases SCM is under predicting the discharge. The present model is found to provide better results for low flow depth cases but for higher flow depth cases, it is giving an error of 5% to 6%.

6.2 Scope of future work

The following are the scope of future work regarding the present work, which may be explored by future researchers.

1. The roughness properties, geometric properties, hydraulic properties of the present experimental asymmetrical compound channel may be modified.
2. The study in this present work is only on rigid bed channels, which may be done on mobile bed channels to understand the difference of flow between rigid channels and mobile bed channels.
3. The modelling for discharge adjustment factor is presented only for straight and rigid compound channels. So for mobile bed channels and meandering channels, the present model may be improved.
4. To make the present model more accurate, more data may be incorporated.

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